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ROLL DIFFUSION BONDING DEVELOPMENT

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By

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ABSTRACT

The object of this study was to extend the state-of-the-art of roll diffusion bonding. Three extremely close fitting packs with different yoke configurations were fabricated, assembled, reduced 60 percent in thickness by hot rolling, and then evaluated.

The test articles showed end separation and deformation of the fabricated part near the sides. These were not a result of yoke geometry or a loose fitting, but appeared to be inherent characteristics from the rolling operation.

NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER

ROLL DIFFUSION BONDING DEVELOPMENT

By

Carl M. Wood

MECHANICAL AND CHEMICAL BRANCH
MANUFACTURING ENGINEERING LABORATORY
RESEARCH AND DEVELOPMENT OPERATIONS

ACKNOWLEDGMENT

The main text of this document is based on a report (MD-204-67) by G. H. Jones, Hayes International Corporation, prepared under the technical direction of Carl M. Wood, R-ME-MM, Manufacturing Research and Technology Division, Manufacturing Engineering Laboratory, George C. Marshall Space Flight Center, Huntsville, Alabama.

The Appendix is taken from Manufacturing Development Memorandum R-ME-M-21-67 by Earl A. Hasemeyer, R-ME-MW, Manufacturing Research and Technology Division.

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ROLL DIFFUSION BONDING DEVELOPMENT

SUMMARY

Excellent potential is offered by roll diffusion bonding for joining similar and dissimilar metal combinations for aerospace applications. This program was established to advance the state-of-the-art in roll diffusion bonding as a fabricating technique for high strength alloys. The task was to design, fabricate, and test three titanium panels using different yoke concepts to supplement the work done under contract by North American Rockwell for MSFC.

Two new yoke designs were used to establish whether end separation and deformation of the "T" stiffener were caused by yoke design or loose fitting packs, or were inherent characteristics of the rolling operation.

The conclusion reached was that the end separation and deformation of the part at the outside edge were caused by the rolling operation and not by a loose fitting pack. Design of the yoke had no significant effect on the end separation and straightness of the final part.

INTRODUCTION

The design of minimum-weight high-performance structures for aerospace applications requires efficient and reliable methods for joining similar and dissimilar metal combinations. Roll diffusion bonding appears to offer excellent potential for joining and, in certain cases, it is the only feasible process. This program was established to advance the state-of-the-art in roll diffusion bonding as a fabricating technique for high strength alloys by fabricating simulated skin sections from 8Al-1Mo-1V titanium alloy.

The task was to design, fabricate, and test three 30.5 cm by 122 cm (12 in. by 48 in.) panels using two new yoke designs along with one of conventional design for comparison. This effort was coordinated with North American Rockwell to supplement the work they did for MSFC on a similar effort under Contract No. NAS8-20530.* As originally planned, the program at MSFC called for fabricating

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* Final report, Simulated Titanium S-IC Skin Section By North American Rockwell Corporation, Rpt. No. NA-67-458.

six packs as a two-phase program. Three packs would be fabricated in the first phase and the information gained during the first phase would be used in fabricating three additional packs as the second phase. No plans have been made to carry out the second phase. Consequently, this report deals only with the initial three packs.

The subscale packs measured 21.6 cm × 45.7 cm × 60.9 cm (8.5 in. × 18 in. × 24 in.) prior to rolling and after heating to 1275°K (1835°F) and rolling to 60 percent reduction in thickness, the packs measured approximately 8.25 × 45.7 cm × 152 cm (3.25 in. × 18 in. × 60 in.).

The two new yoke designs were used to establish whether the characteristics of end separation and deformation of the "T" stiffener were caused by yoke design or loose fitting packs, or were inherent characteristics from the rolling operation. The third pack, of conventional design, was used as a basis of comparison (Fig. 1, 2, and 3). Dimensional tolerance and surface finish in the areas of significance were the best normally obtained by conventional machining methods with standard equipment. In most cases the tolerances were ± 0.0254 mm (± 0.001 in.) maximum. Yoke and filler bars were made of AISI 1050 carbon steel which contained the minimum carbon content to prevent the steel and titanium from bonding.

OPERATIONS

Design of Packs

Packs were designed to produce a minimum weight panel of moderate complexity to supplement the research program conducted by North American Rockwell under contract NAS8-20530. The two programs were coordinated to prevent duplication of efforts.

Areas of study included in the design of the packs were:

1. Establish whether distortion at the sides of the parts was caused by a loose fitting pack or whether the characteristic was inherent from the rolling operation.

2. Establish whether an extremely close fitting pack would bring the quality of bond at the last 10.2 cm (4 in.) of the two ends up to the level of the remainder of the pack.

3. Determine whether the separation between yoke and filler bars at the ends (approximately 6.35 mm - 0.250 in.) would be decreased with a change in yoke configuration.

4. Study the effect filler bar radii have on the formed titanium fillet.

All three yokes were 15.2 cm × 45.7 cm × 60.9 cm (6 × 18 × 24 in.) outside dimensions with 3.17-cm (1.250-in.) thick face plates on the top and bottom. One yoke was made of solid material with minimum material removed to insert the titanium parts and obtain a tight fit. Another yoke was diamond shaped to give a configuration that would decrease the end separation between filler bars and yoke. The third yoke was of conventional rectangular shape to use for comparison.

Filler bars, yokes, and cover plates were made of AISI 1050 carbon steel instead of the AISI 1018 carbon steel used by North American Rockwell. This steel was selected because some current literature indicated that steel containing 0.50 percent or more carbon would not bond to Ti-8Al-1Mo-1V. No high purity titanium sheets were used under the cover plates to prevent bonding of the face plates to the titanium parts and filler bars.

Dimensional tolerances and surface finishes specified on the packs were the closest that could be obtained with conventional equipment in the areas where tolerances were significant. In most cases the tolerances were ±0.0254 mm (± 0.001 in.) and the surface finish at the bonding interfaces was 2 μm RMS (8 RMS).

Assembly of Packs

Prefit. Prior to final cleaning for pack lay-up, all titanium and tooling details were measured and prefitted to make sure the parts went together according to drawings MR&T-SK-1114, MR&T-SK-1115, and MR&T-SK-1116. Parts were cleaned with methylethyl ketene and/or acetone to remove the light protective coat of oil for prefitting. No chlorinated solvents were permitted to come into contact with any of the parts. Grinding was required on some of the parts to obtain the desired fit. Measurements were taken on the packs during prefit to determine how well they fit. Three checks were made across the filler bars and the accumulated blank space varied from 0.305 to 0.483 mm (0.012 to 0.019 in.). This gave packs with a minimum solid content of 99.8 percent.

Cleaning. After prefit and prior to lay-up of the packs, all filler bars, cover plates, yokes, and titanium parts were cleaned to remove all visible contamination such as oxides, dirt, oil, and grease. Titanium parts were acid cleaned in a solution of 35 percent nitric acid — 5 percent hydrofluoric acid followed by deionized water rinse and oven drying. Steel details were wiped with methylethyl ketone, alkaline cleaned in a solution of 8 ounces per gallon of Altrex X, water rinsed, and oven dried.

After cleaning, all parts were handled with clean plastic gloves. Cleaned titanium details were protected with dust-free neutral kraft paper wrappings. Cleaned steel details were protected by polyethylene bags.

Lay-Up. Pack lay-ups were performed in a dust-free area within 48 hours after cleaning, (Fig. 4 through 12). All personnel engaged in the lay-up operation were required to wear clean plastic gloves when handling parts. Only descaled and clean metallic tooling was used inside the pack containing the part. No graphite, ceramics, or other non-metallics which give off contaminants were permitted. Immediately following lay-up, the top cover was positioned for fusion welding.

Welding. Welding operations were conducted outside the clean room. The welding of cover plates and yokes was performed in accordance with the requirements of specification ABMA-PD-R-27A, Class II Radiographic. The internal cavity of the packs was shielded by commercially pure helium during the welding and the protection was continued until all parts were cooled to 589°K (600°F) maximum. After welding, the packs were subjected to a leak check to make sure no leak exceeded 1×10^{-4} cubic centimeters per second of helium when subjected to a pressure of 1.37×10^5 N/m^2 (20 psig).

Purging. Purge lines were fabricated from 12.7 mm OD × 0.889 mm wall (0.500 in. OD × 0.035 in. wall), type AISI 321 stainless steel tubing. A single purge cycle consisted of evacuating the packs to 3320 N/m^2 (25 mm of mercury) and backfilling with argon until a slight positive pressure existed within the pack. Each pack was purged at room temperature a minimum of 5 cycles prior to hot purging.

Packs were heated to 922°K (1200°F) and held for an hour to remove volatile matter in the metal of the yoke cavity (Fig. 13 and 14). During heating the packs were continuously purged. Packs were filled with argon to a positive pressure of approximately 1.01×10^5 N/m^2 (14.7 psi) at room temperature and the vacuum valve was closed and capped for shipment.

Hot Rolling Packs

Hot rolling of the packs to achieve 60 percent reduction in thickness was performed by Union Carbide, Y-12 Plant, Oak Ridge, Tennessee. The packs were heated to 1275°K (1835°F), soaked for approximately 8 hours, and reduced by rolling to 60 percent in 10 passes. Elapsed time between discharging the packs from the furnace and completing the rolling operation varied from 2.5 minutes to 6.9 minutes. A solid piece of steel the same size as the packs was rolled immediately before the packs to heat the rolls and familiarize personnel with the handling procedure and recording of data.

To prevent slippage between the packs and rolls on the first pass, one end of each pack was tapered at 0.787 radians (45° angle) by burning the top and bottom edges off approximately 3.17 cm (1.250 in.).

During the second rolling pass on each pack, the face plate separated slightly from the yoke causing a loss of vacuum in the pack. Further rolling closed the opening but it was felt that the loss of vacuum at this point contributed to some of the lack of bonding of the titanium parts. Since the same thing happened to all three packs, it was felt that the rolling conditions rather than faulty welding caused the separation. The conveyor bed was 7.6 cm (3 in.) below the bottom roll and while the packs were short, sufficient twisting was exerted to cause the separation. Immediately after the last reduction pass, the packs were straightened by sending them through the rolls turned 1.57 radians (90°) to the direction of rolling.

Temperature of the pack after rolling was 1127° to 1164°K (1570° to 1635°F). Drop in temperature to below 755°K (900°F) with air cooling required approximately 15 minutes which was below the maximum to maintain the duplex anneal condition of the Ti-8Al-1Mo-1V alloy.

Data taken during and after the rolling operation are given in Tables I through III and Figures 15 through 17. The packs after rolling are shown in Figures 18.

Removal of Titanium Parts from Packs

The first step in removing the titanium parts from the packs was to burn off as much of the steel with an oxygen - acetylene torch as was considered safe

without damage to the titanium. Approximately 7.62 cm (3 in.) of steel was removed from the sides and about 15.2 cm (6 in.) was removed from the ends.

Pack "A" was selected as the first pack to be taken apart because the face plates appeared to be bonded better than on the other two packs. Two 10.2-cm (4-in.) cross sections were cut from the center of Pack "A" by sawing to establish the method of removing the titanium parts. It was found that the steel was bonded to steel and titanium was bonded to titanium, but the steel was not bonded to the titanium (Fig. 19). This information was used in machining to remove as much of the steel as feasible to decrease the amount of etching.

During machining a separation between the yoke and the part of approximately 6.35 mm (0.250 in.) was found at both ends on all three packs.

Packs "A" and "C" were leached in a solution of 30 percent nitric acid to remove the remaining steel. Titanium parts of Packs "B" were not sufficiently bonded to justify the time-consuming leaching operation. A small stainless steel tank was fabricated for this operation and no circulation of the acid was included. The acid solution was agitated occasionally by raising and lowering the pack in the tanks with the crane. A total of 1110 kg (2500 lb) of acid was required for the leaching operation.

A visual inspection of the parts after removal showed that 10.2 to 15.2 cm (4 to 6 in.) of each end were not bonded.

Removal of the parts from the packs is shown in Figure 20 through 25. Dimensional checks on the cross section of Pack A are shown in Figure 26.

LABORATORY EVALUATION

The bonded Ti-8Al-1Mo-1V panels from Packs A and B were evaluated by R-ME-MW and the results are included in Appendix "A". A summary of these results follows:

1. Mechanical testing of the parts was limited to tensile testing of the base material and of the "T" bonds. Tests showed the bonds in most cases were as strong as the base metal. Ultimate strength of the base material was 98 600 N/cm^2 (143 000 psi).

2. Metallurgical views at 100 and 500 magnifications showed a continuous grain structure across the bond.

3. No surface cracks or contamination of the parent material were found when viewed at magnifications up to 500X.

4. There was practically no correlation between the radii of the steel filler bars and radii of the formed titanium fillets. Practically all of the formed titanium fillets were unsatisfactory.

CONCLUSIONS

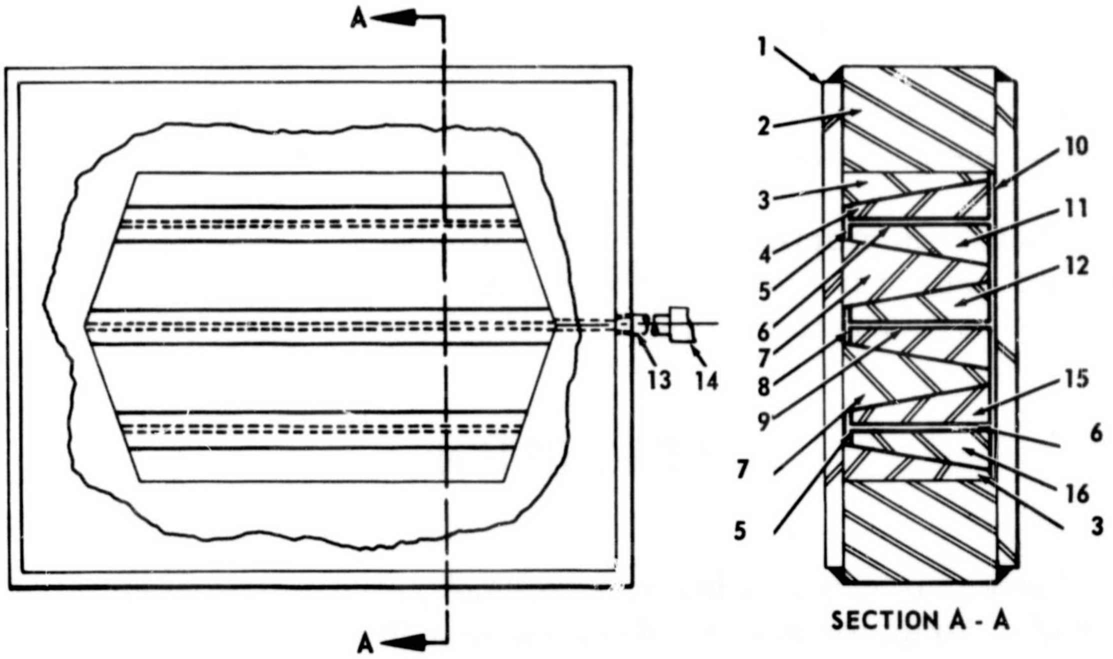
1. Extremely close fitting packs did not prevent distortion to the parts near the sides. No distortion was observed near the center.

2. The diamond shaped yoke and near solid yoke did not prevent separation between part and yoke during the rolling operation.

3. The radii of the filler bars have no significant effect on controlling the fillet radii at the formed titanium "T" joints.

4. AISI 1050 carbon steel did not bond to Ti-8Al-1Mo-1V and no contamination of the titanium resulted from the use of this steel.

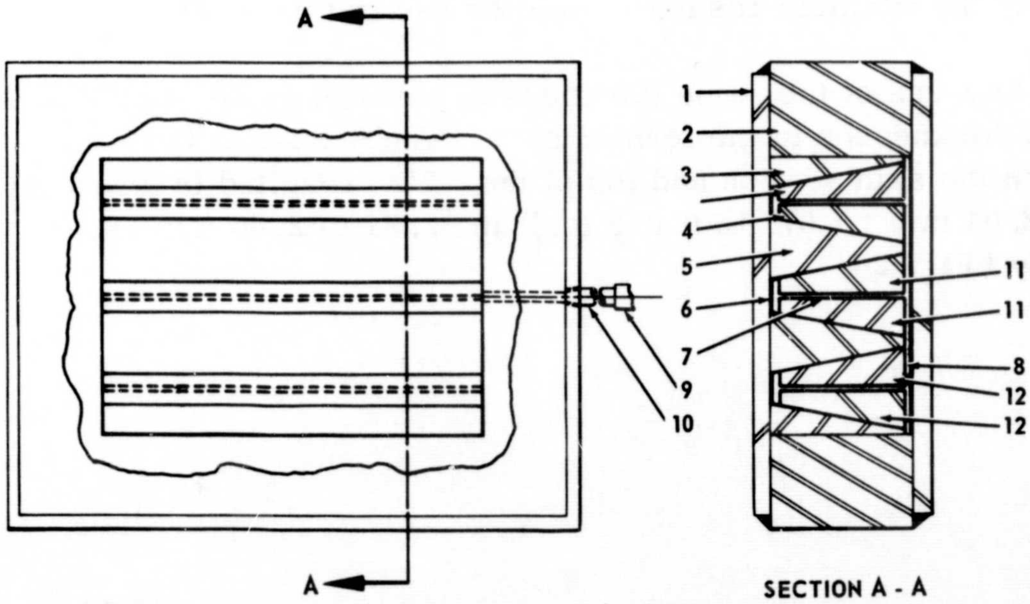
5. Lay-ups of the same thickness in parallel planes resulted in segments of different thicknesses in the formed part. The 6.35-mm (0.250-in.) thick plate used in the skin section and top of the "T's" resulted in a final part thickness of 1.96 to 2.01 mm (0.077 to 0.079 in.) and 2.31 to 2.46 mm (0.091 to 0.097 in.) respectively (Fig. 26).



LEGEND:

1. PLATE
2. BODY
3. SIDE FILLER BAR
4. FILLER BAR
5. TOP
6. WEB
7. WEDGE
8. CENTER TOP
9. CENTER WEB
10. BASE
11. SHORT FILLER BAR
12. CENTER FILLER BAR
13. NIPPLE, LONG 1/2 NPT X6" LG.
14. VALVE 154-1/2 SS REPUBLIC
15. FILLER BAR
16. FILLER BAR

FIGURE 1. ROLL DIFFUSION BONDING PACK "A" (DRAWING MR&T-SK-1114)



LEGEND:

1. PLATE
2. BODY
3. SIDE FILLER BAR
4. FILLER BAR
5. WEDGE FILLER BAR
6. TOP
7. WEB
8. BASE
9. VALVE 154-1/2 SS REPUBLIC
10. NIPPLE, LONG 1/2 NPT X6" LG.
11. FILLER BAR
12. FILLER BAR

FIGURE 2. ROLL DIFFUSION BONDING PACK "B" (DRAWING MR&T-SK-1115)

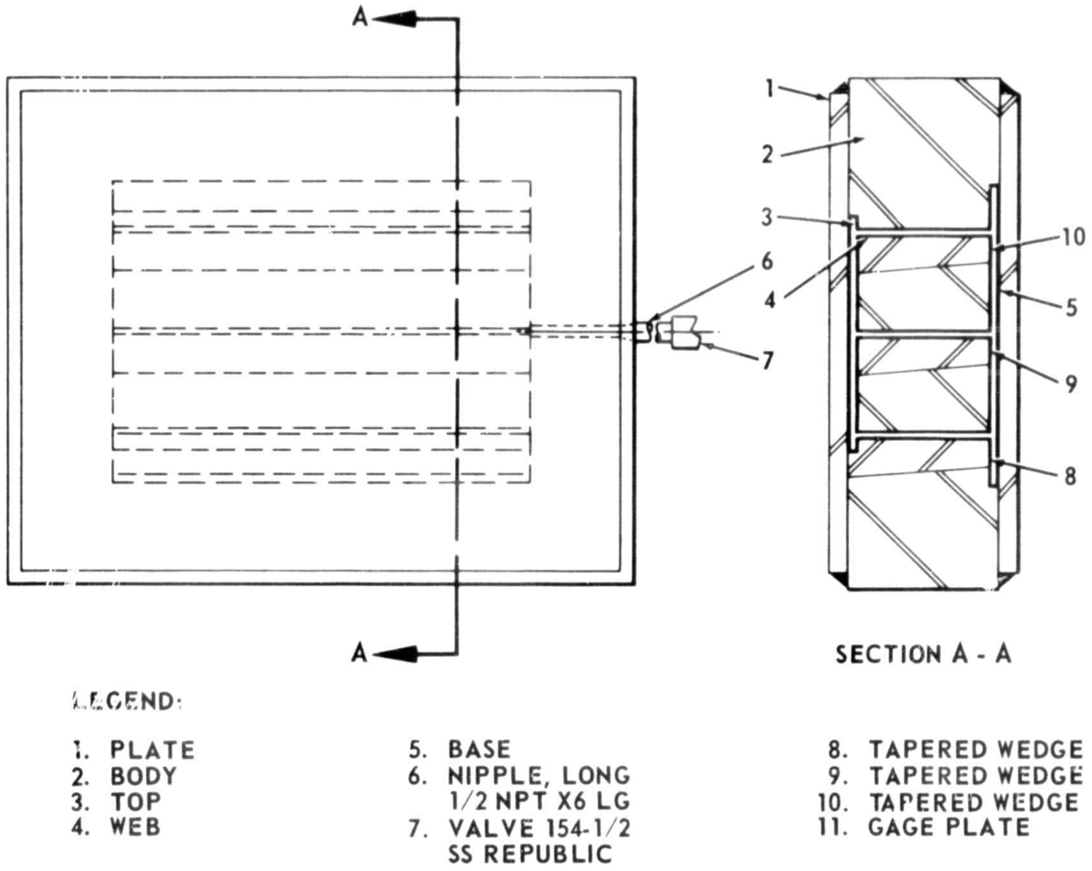


FIGURE 3. ROLL DIFFUSION BONDING PACK "C" (DRAWING MR&T-SK-1116)

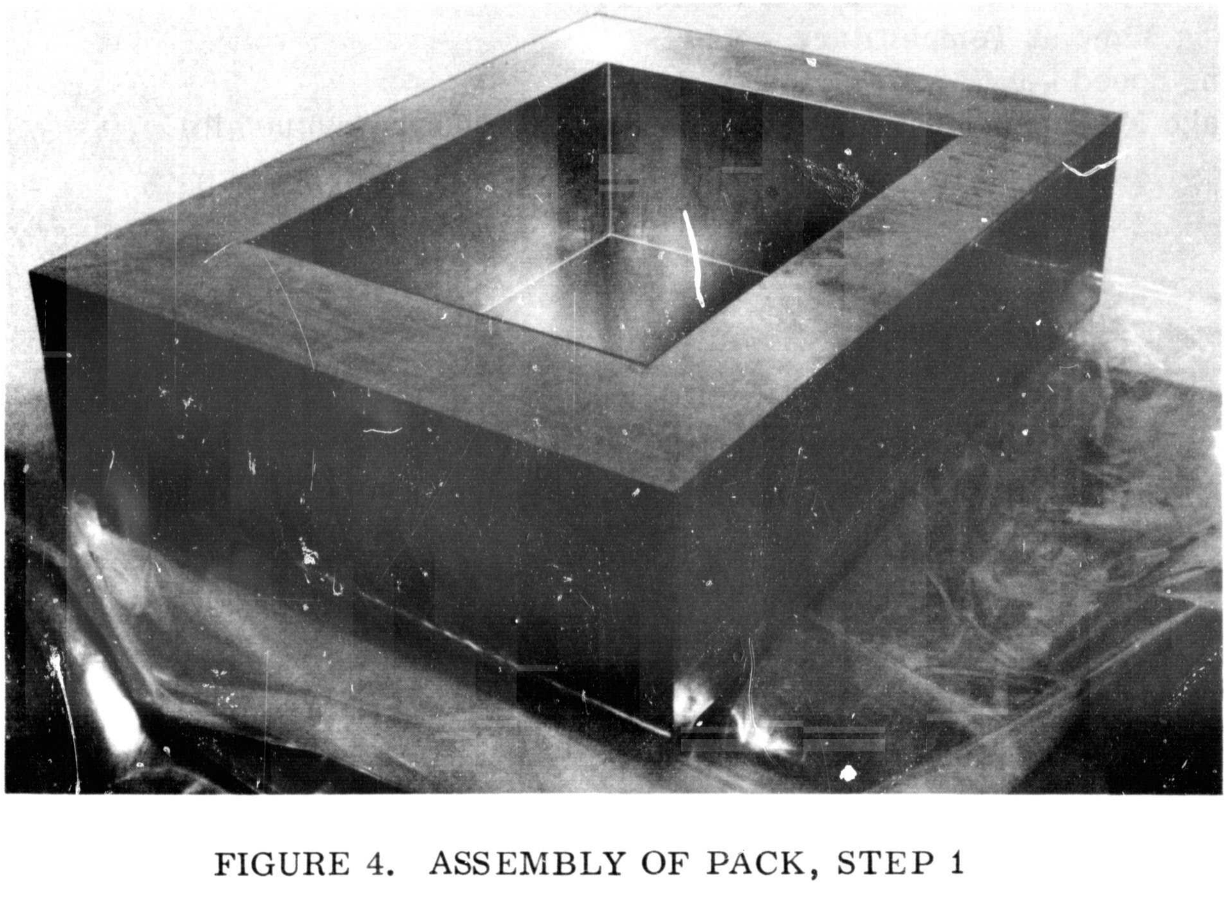


FIGURE 4. ASSEMBLY OF PACK, STEP 1

TABLE I. HOT ROLLING PACK A

Pass No.	Thickness after pass		Temperature after pass*		Time Lapse after pack discharged from furnace, min
	cm	in.	°K	°F	
1	19.93	7.850	1120	1560	1.2
2	17.78	7.000	1103	1525	1.6
3	15.95	6.280	1139	1690	2.0
4	14.35	5.650	1147	1605	2.3
5	12.88	5.075	1153	1615	2.7
6	11.56	4.555	1150	1610	3.0
7	10.41	4.100	1150	1610	3.4
8	9.35	3.680	1150	1610	3.7
9	8.43	3.320	1150	1610	4.0
10	8.25	3.250	1150	1610	4.3

* Temperatures were checked during rolling with an optical pyrometer.

Furnace Temperature - 1275°K (1835°F)
Pack Temperature - 1275°K (1835°F)
Soaking Time at Temperature - 8 hr
Rolling Speed - 0.762 m/s (150 ft/min)
Average Maximum Pressure Per Pass - 1 110 000 N (250 000 lb)

TABLE II. HOT ROLLING PACK B

Pass No.	Thickness after pass		Temperature after pass*		Time Lapse after pack discharged from furnace, min
	cm	in.	°K	°F	
1	19.93	7.785	1183	1670	0.4
2	17.78	7.000	1158	1625	0.6
3	15.95	6.280	1147	1605	0.8
4	14.35	5.650	1147	1605	1.1
5	12.88	5.075	1158	1625	1.3
6	11.56	4.555	1166	1640	1.6
7	10.41	4.100	1164	1635	1.8
8	9.35	3.680	1164	1635	2.0
9	8.43	3.320	1164	1635	2.3
10	8.25	3.250	1164	1635	2.5

* Temperatures were checked during rolling with an optical pyrometer.

Furnace Temperature - 1275°K (1835°F)
Pack Temperature - 1275°K (1835°F)
Soaking Time at Temperature - 8 hr
Rolling Speed - 0.762 m/s (150 ft/min)
Average maximum pressure per pass - 1 100 000 N (250 000 lb)

TABLE III. HOT ROLLING PACK C

Pass No.	Thickness after pass		Temperature after pass*		Time Lapse after pack discharged from furnace, min
	cm	in.	°K	°F	
1	19.93	7.785	1119	1555	3.0
2	17.78	7.000	1114	1545	3.4
3	15.95	6.280	1114	1545	3.9
4	14.35	5.650	1114	1545	4.3
5	12.88	5.075	1133	1580	4.7
6	11.56	4.550	1127	1570	5.2
7	10.41	4.100	1127	1570	5.6
8	9.35	3.680	1127	1570	6.0
9	8.43	3.320	1127	1570	6.5
10	8.25	3.250	1127	1570	6.9

*Temperatures were checked during rolling with an optical pyrometer.

Furnace Temperature - 1275°K (1835°F)
Pack Temperature - 1275°K (1835°F)
Soaking Time at Temperature - 8 hr
Rolling Speed - 0.762 m/s (150 ft/min)
Average maximum pressure per pass - 1 100 000 N (250 000 lb)

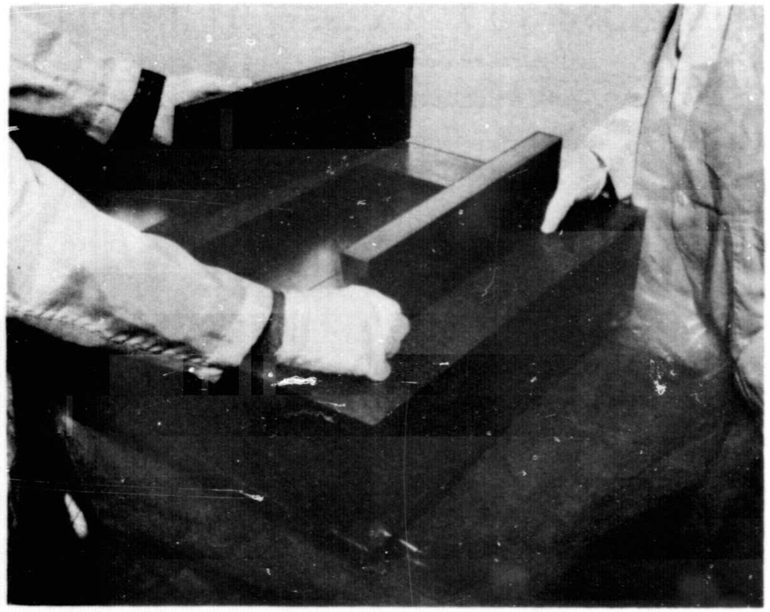


FIGURE 5. ASSEMBLY OF PACK, STEP 2

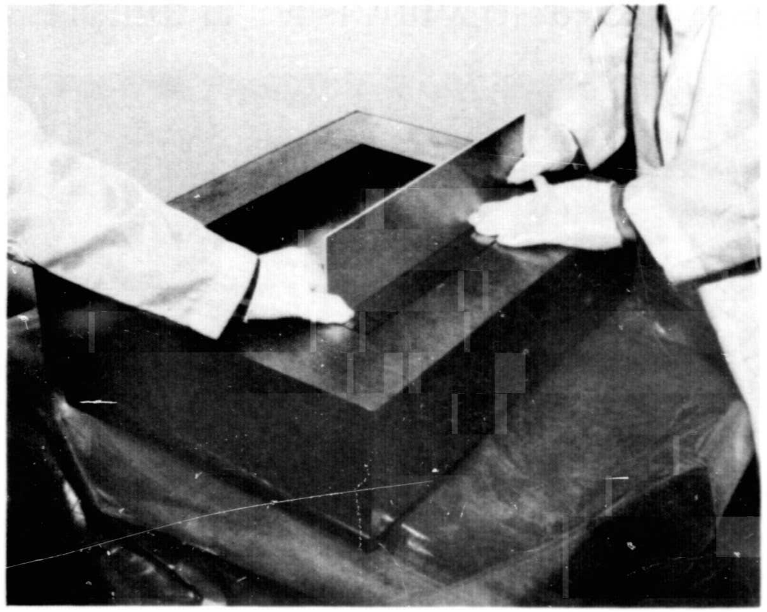


FIGURE 6. ASSEMBLY OF PACK, STEP 3

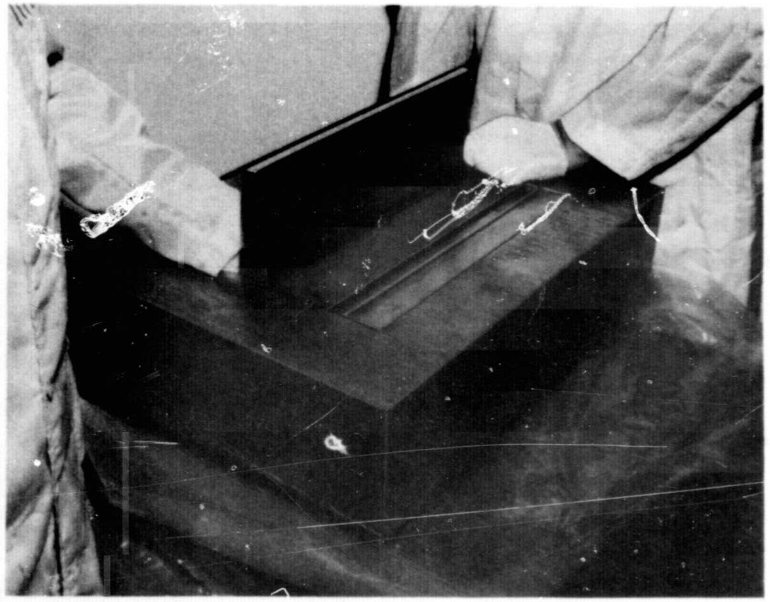


FIGURE 7. ASSEMBLY OF PACK, STEP 4

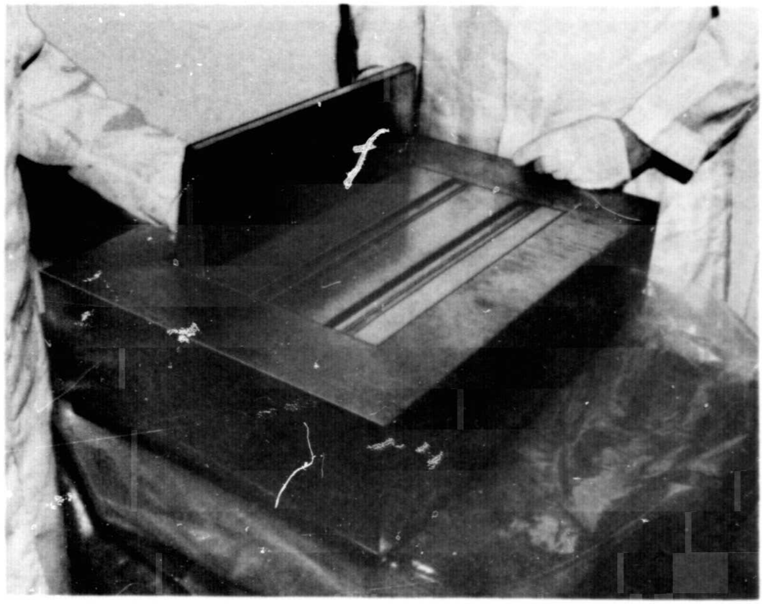


FIGURE 8. ASSEMBLY OF PACK, STEP 5

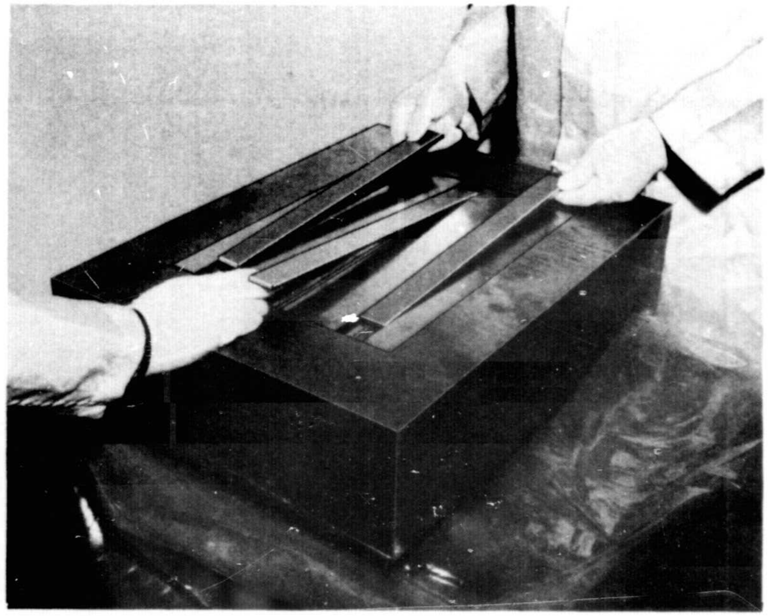


FIGURE 9. ASSEMBLY OF PACK, STEP 6

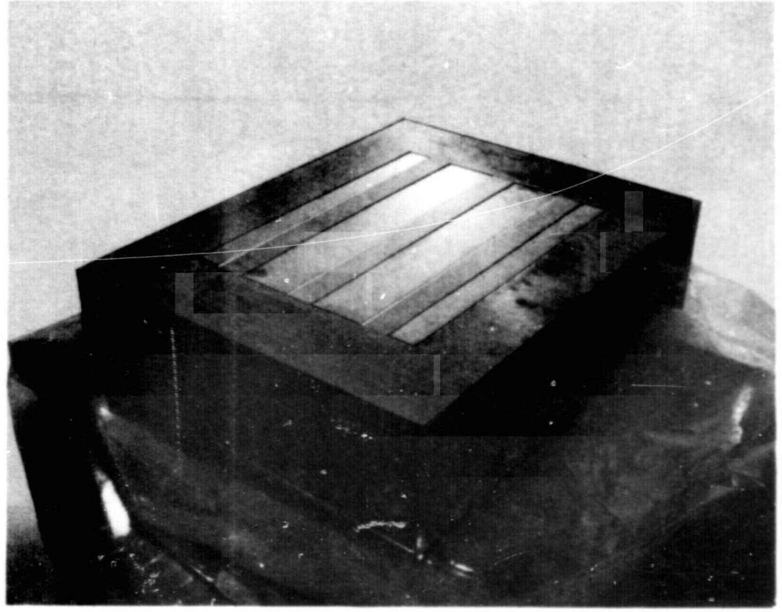


FIGURE 10. ASSEMBLY OF PACK, STEP 7

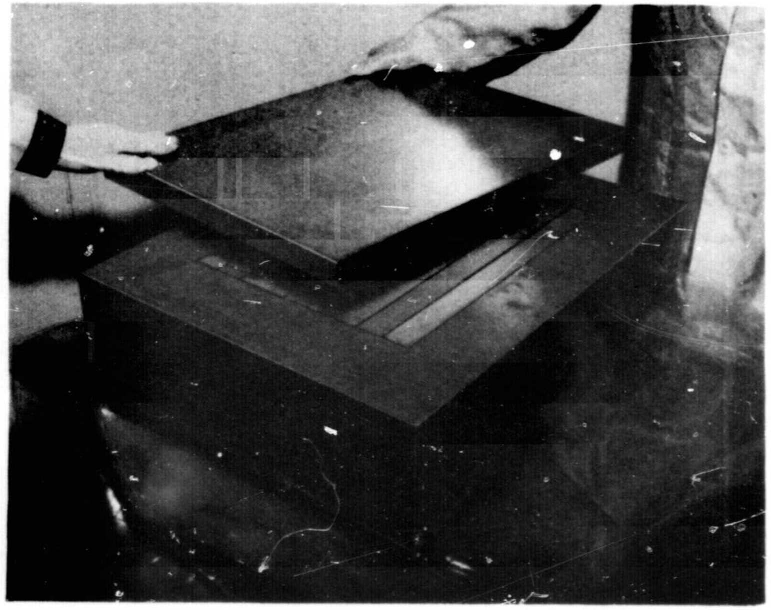


FIGURE 11. ASSEMBLY OF PACK, STEP 8

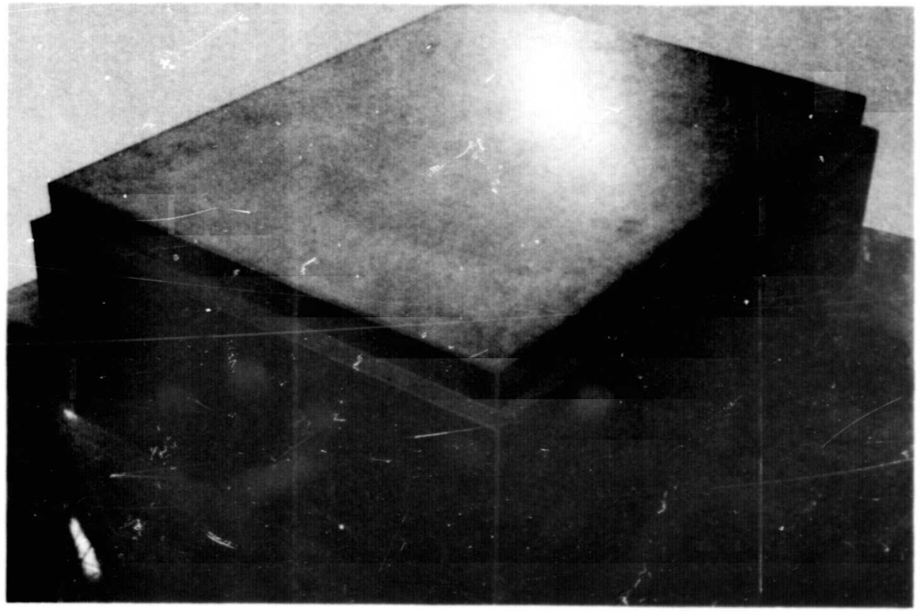


FIGURE 12. ASSEMBLY OF PACK, STEP 9

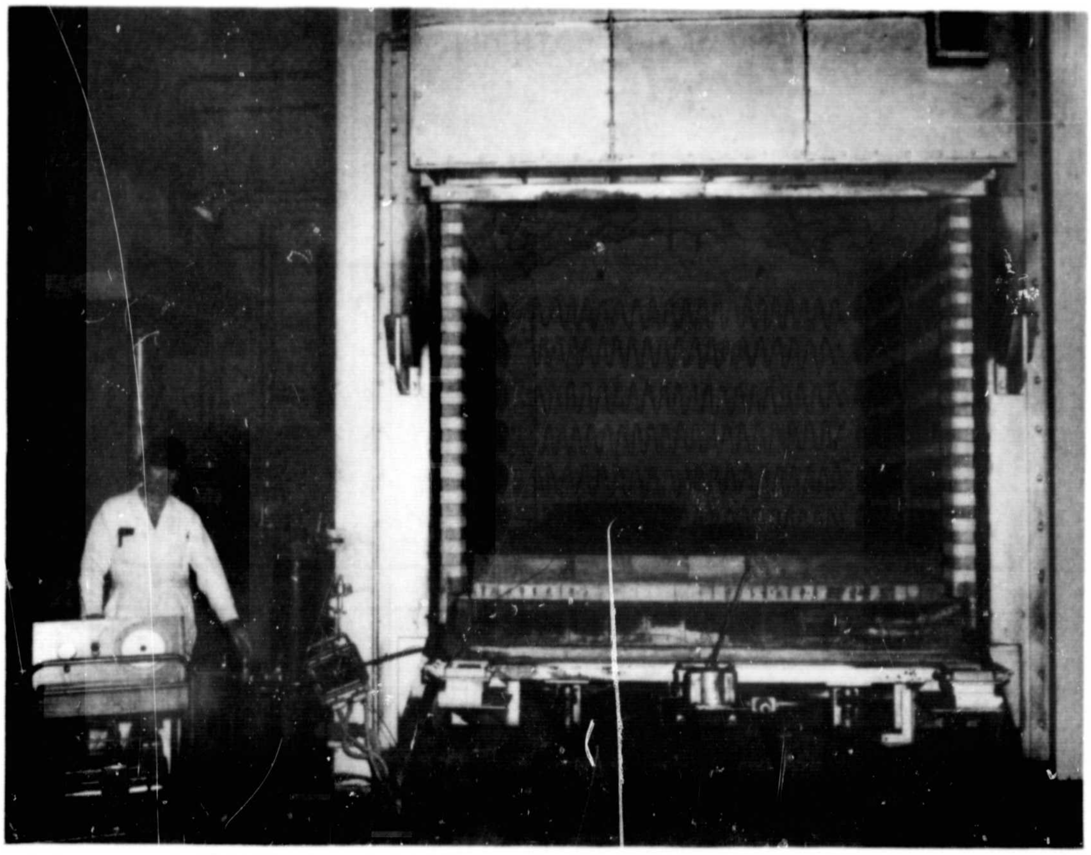


FIGURE 13. PURGING SETUP

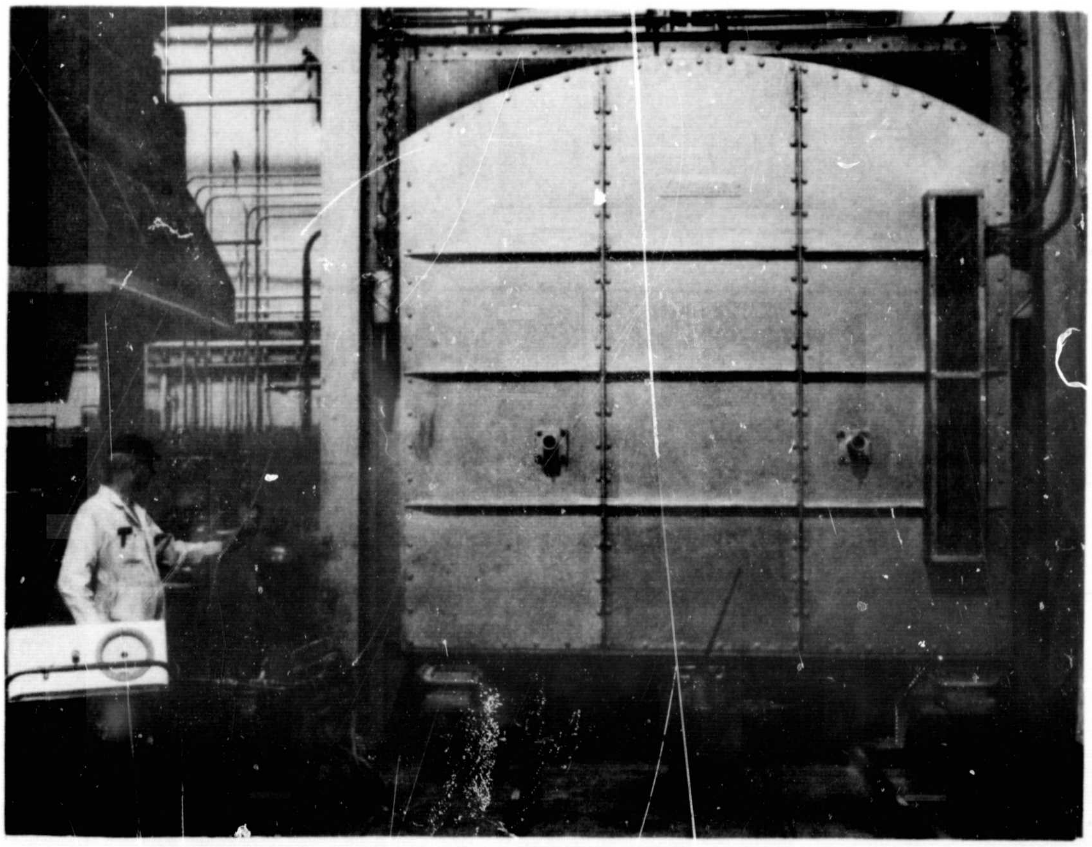
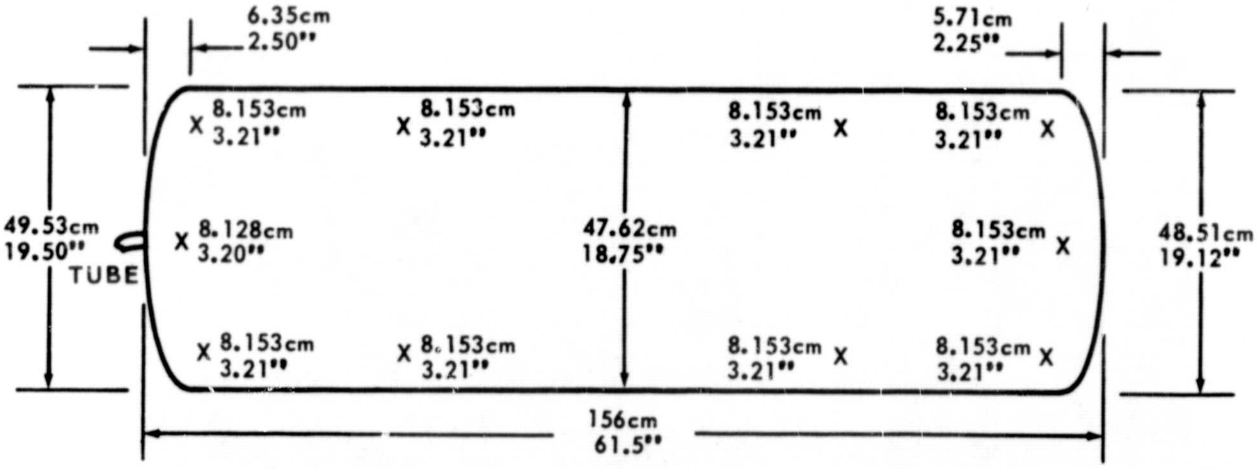


FIGURE 14. DEGASSING OF PACK

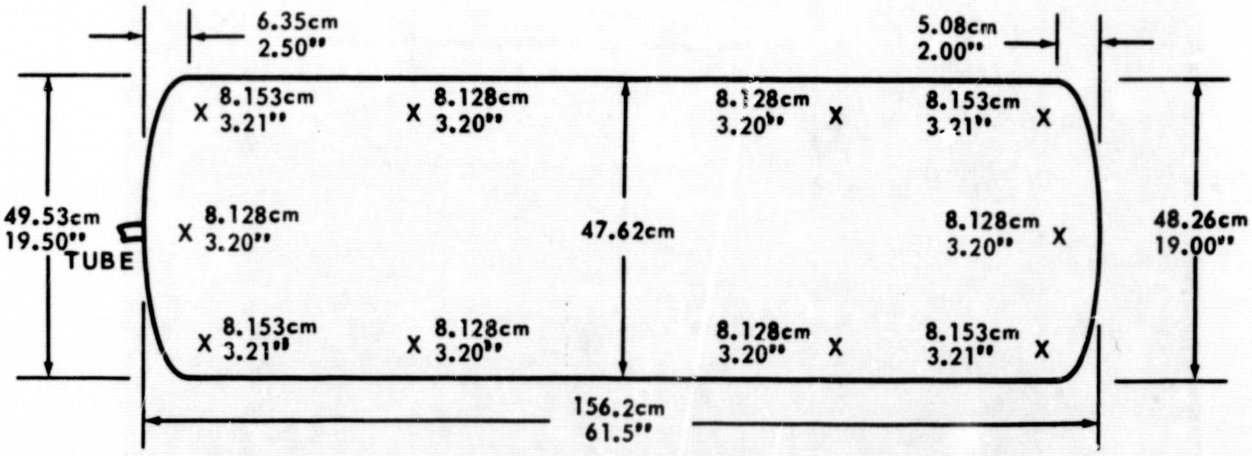
SCHEMATIC OF PACK "A" SHOWING THICKNESS MEASUREMENTS AFTER ROLLING PLUS LENGTH AND WIDTH DIMENSIONS.



FLATNESS OF PACK: MAXIMUM DEVIATION FROM SURFACE PLATE WAS LESS THAN 0.317cm (0.125")

FIGURE 15. MEASUREMENTS ON PACK A, AFTER ROLLING

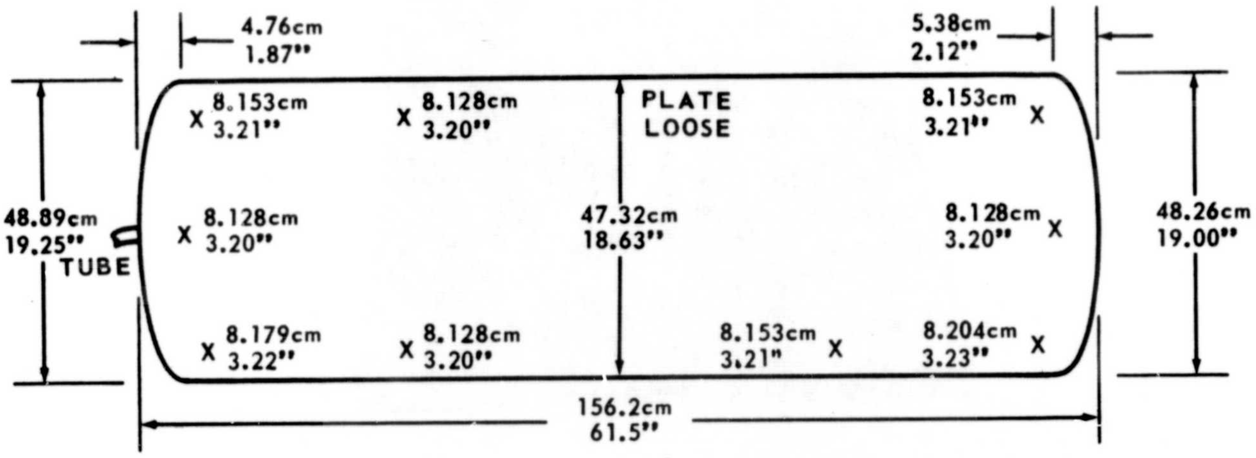
SCHEMATIC OF PACK "B" SHOWING THICKNESS MEASUREMENTS AFTER ROLLING PLUS LENGTH AND WIDTH DIMENSIONS.



FLATNESS OF PACK: MAXIMUM DEVIATION FROM SURFACE PLATE WAS LESS THAN 0.317cm (0.125")

FIGURE 16. MEASUREMENTS ON PACK B, AFTER ROLLING

SCHEMATIC OF PACK "C" SHOWING
THICKNESS MEASUREMENTS AFTER ROLLING
PLUS LENGTH AND WIDTH DIMENSIONS.



FLATNESS OF PACK: MAXIMUM DEVIATION
FROM SURFACE PLATE WAS LESS
THAN 0.317 cm (0.125")

FIGURE 17. MEASUREMENTS ON PACK C, AFTER ROLLING

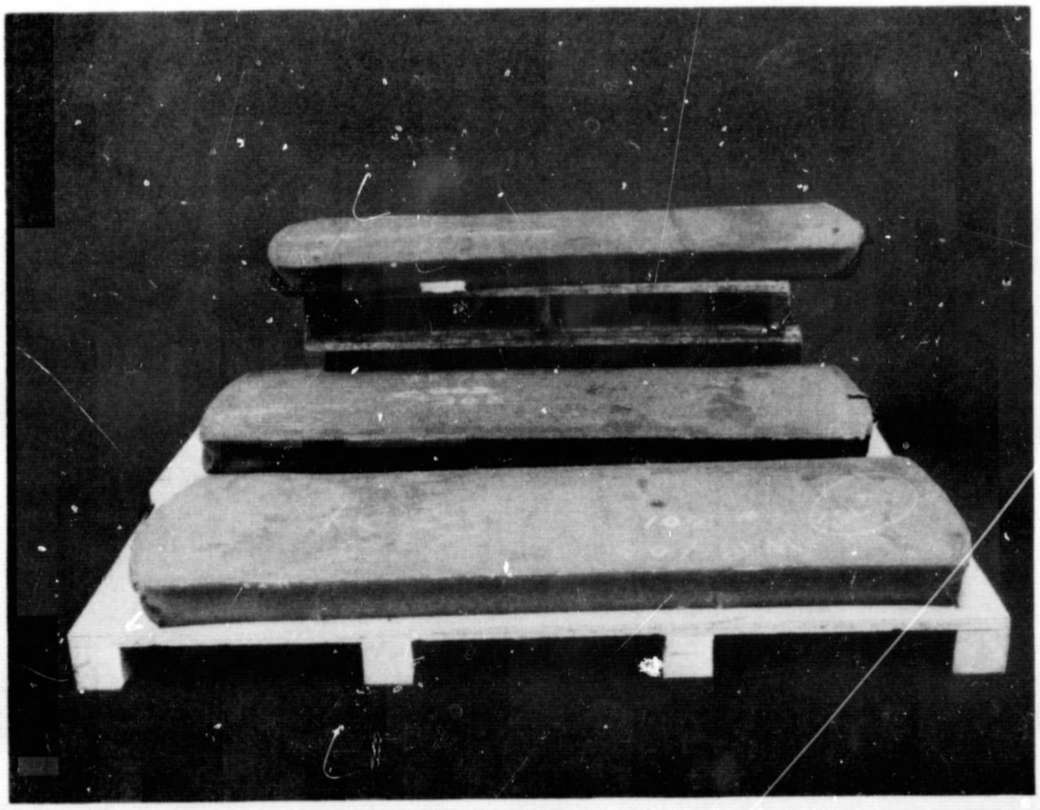


FIGURE 18. PACKS A, B AND C AFTER ROLLING, BOTTOM SIDE

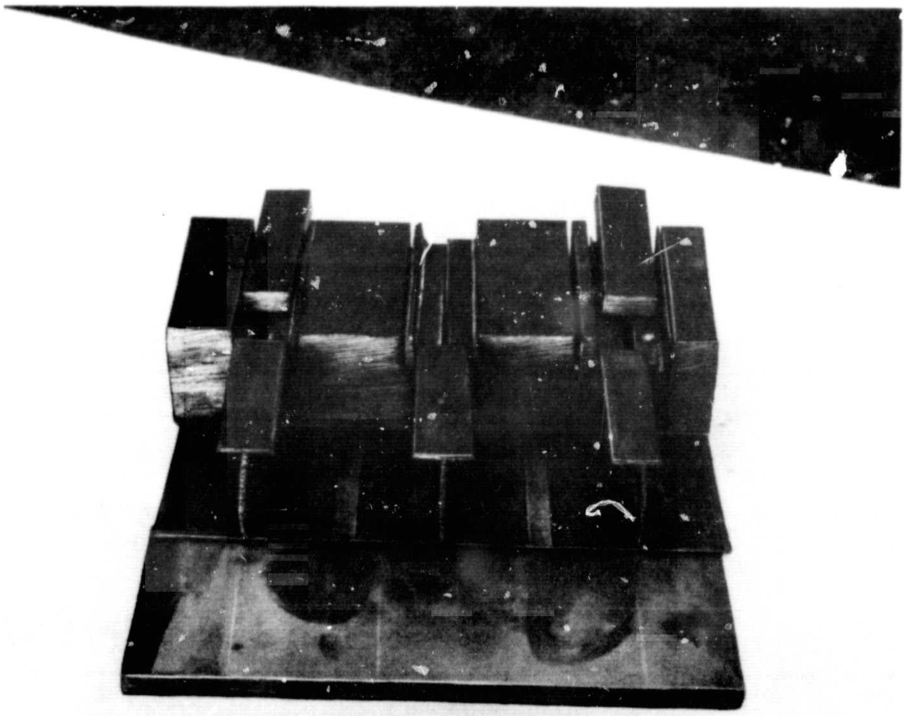


FIGURE 19. REMOVING TITANIUM PART FROM 4-INCH SECTION

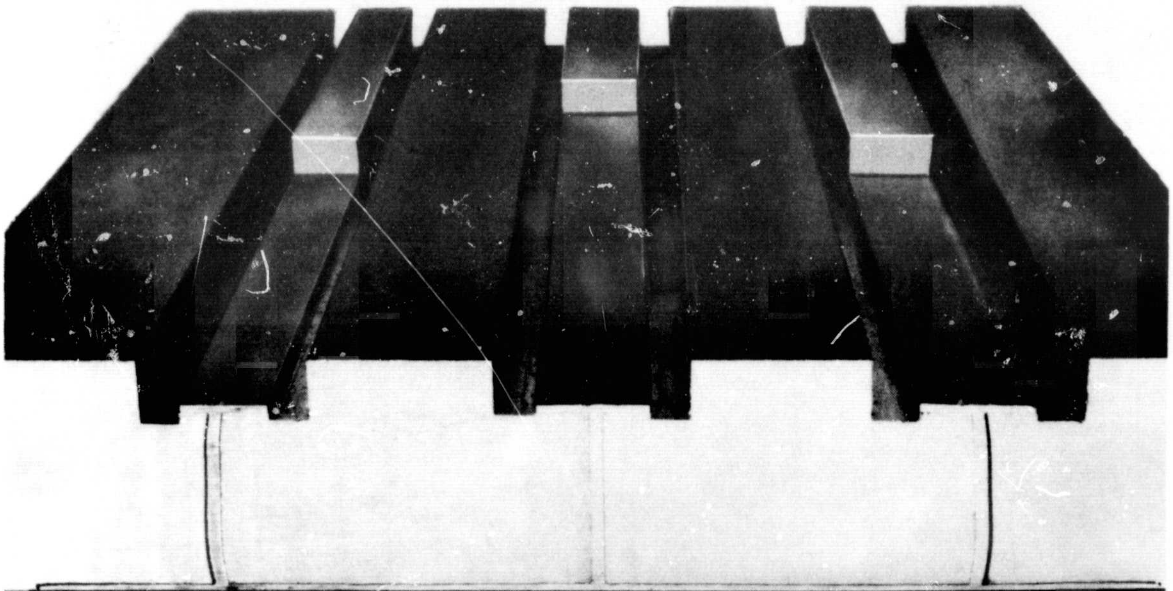


FIGURE 20. PACK A END VIEW SHOWING TITANIUM PART

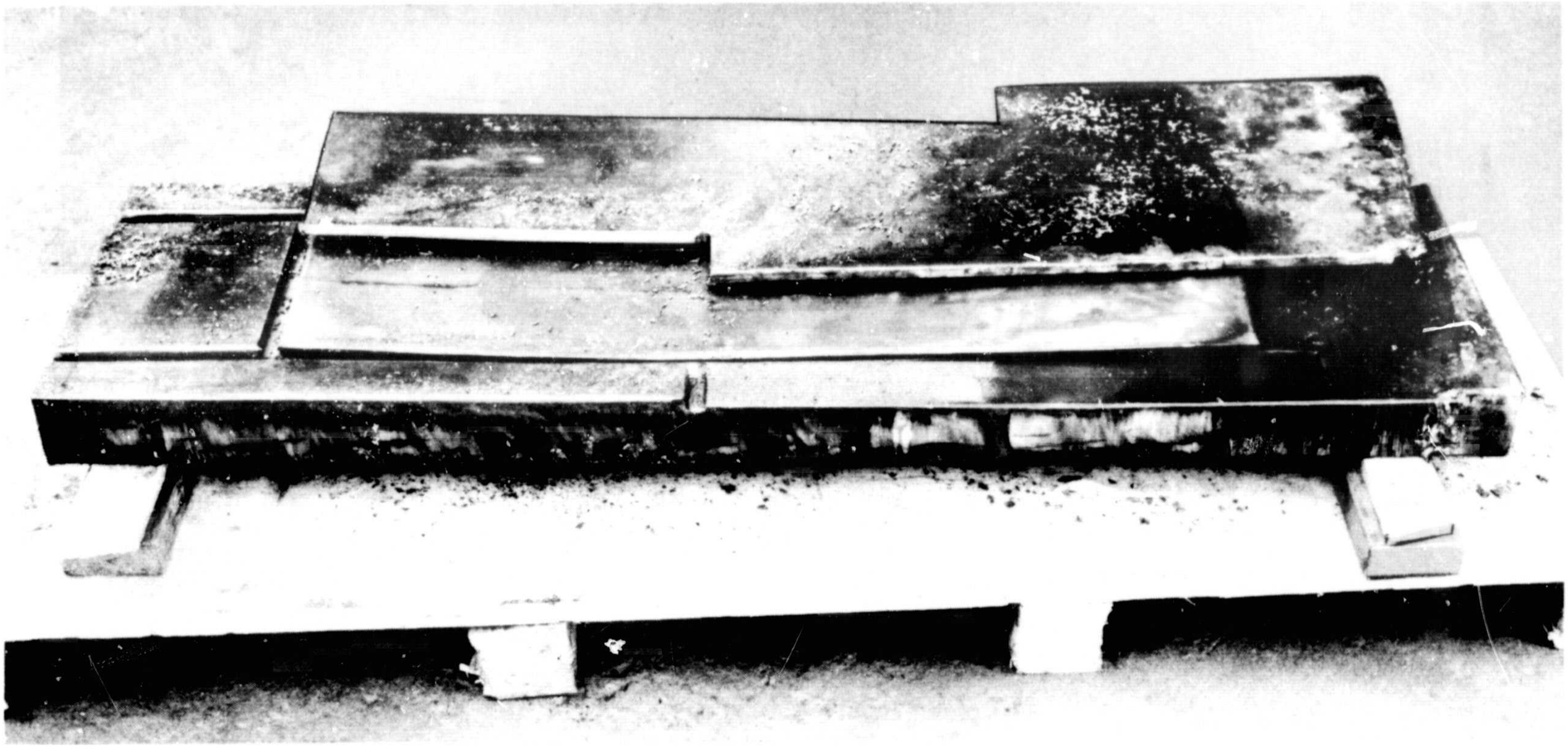


FIGURE 21. PACK B SHOWING FACE PLATE NOT BONDED TO RIBS

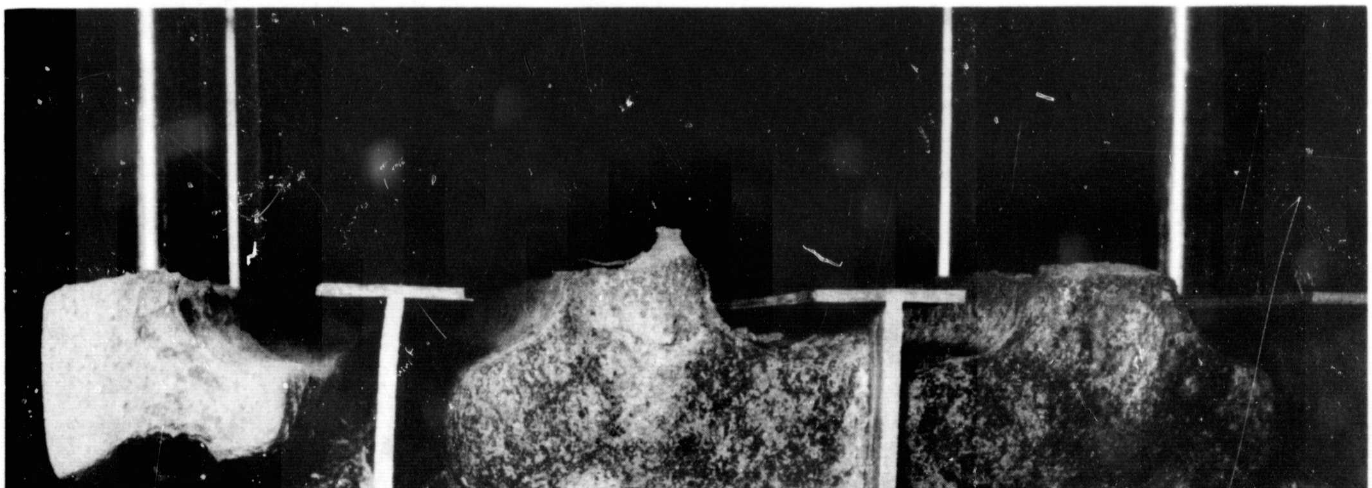


FIGURE 22. PACK A SHOWING UNEQUAL ETCH RATE

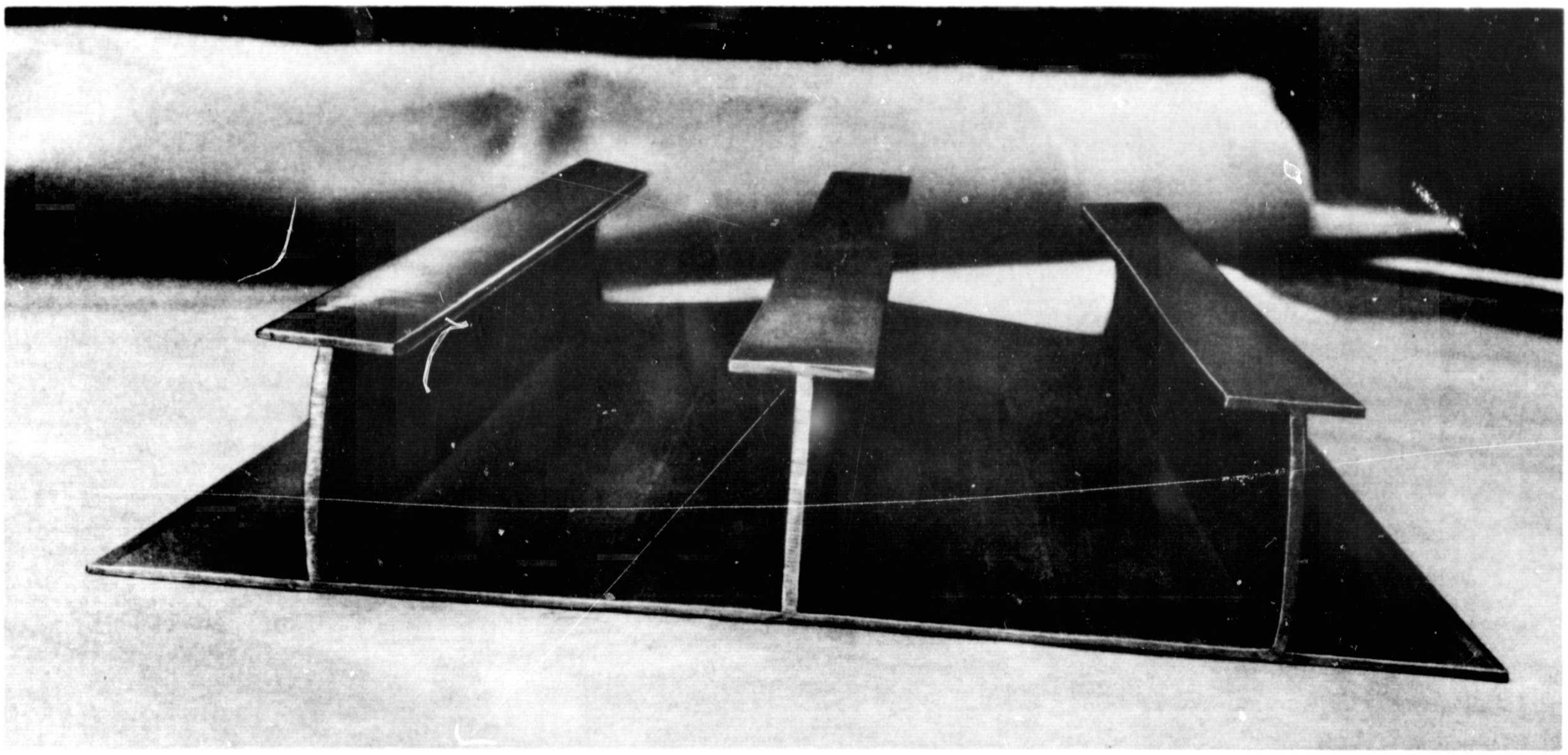


FIGURE 23. CROSS SECTION VIEW OF TITANIUM PART FROM PACK A SHOWING BOW IN TWO OUTER "T" STIFFNESS

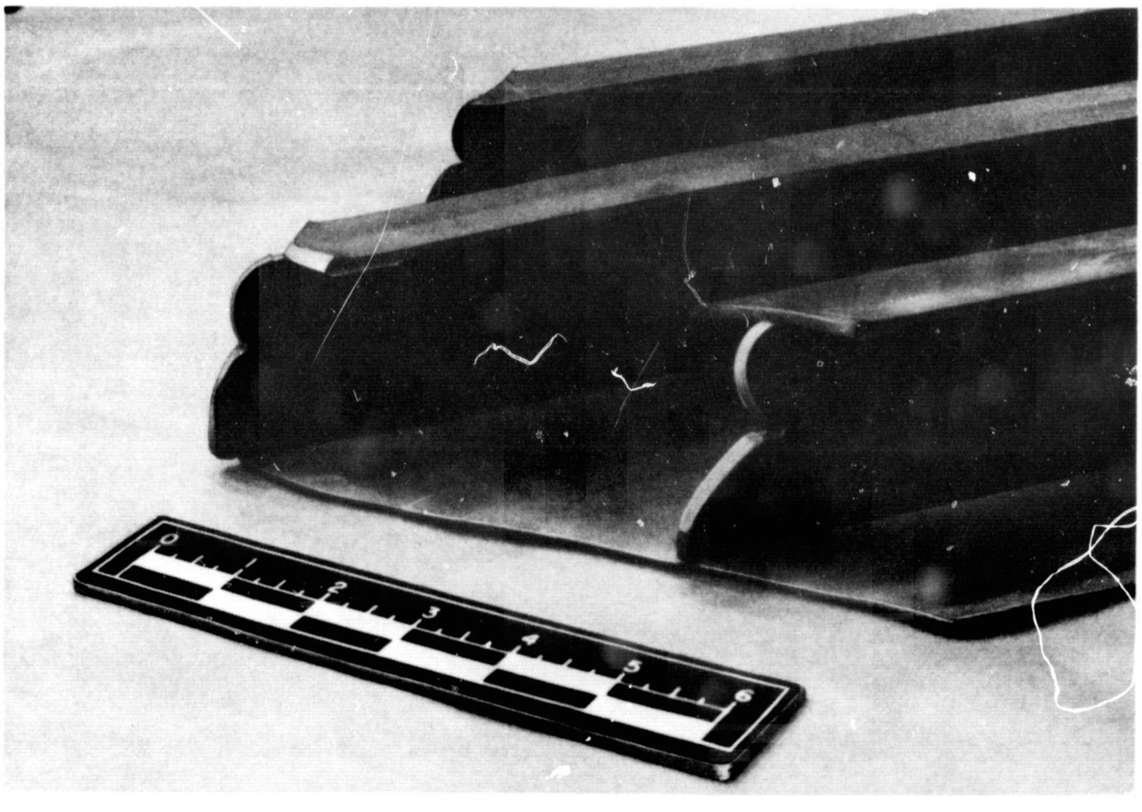


FIGURE 24. VIEW OF PACK A END CONFIGURATION

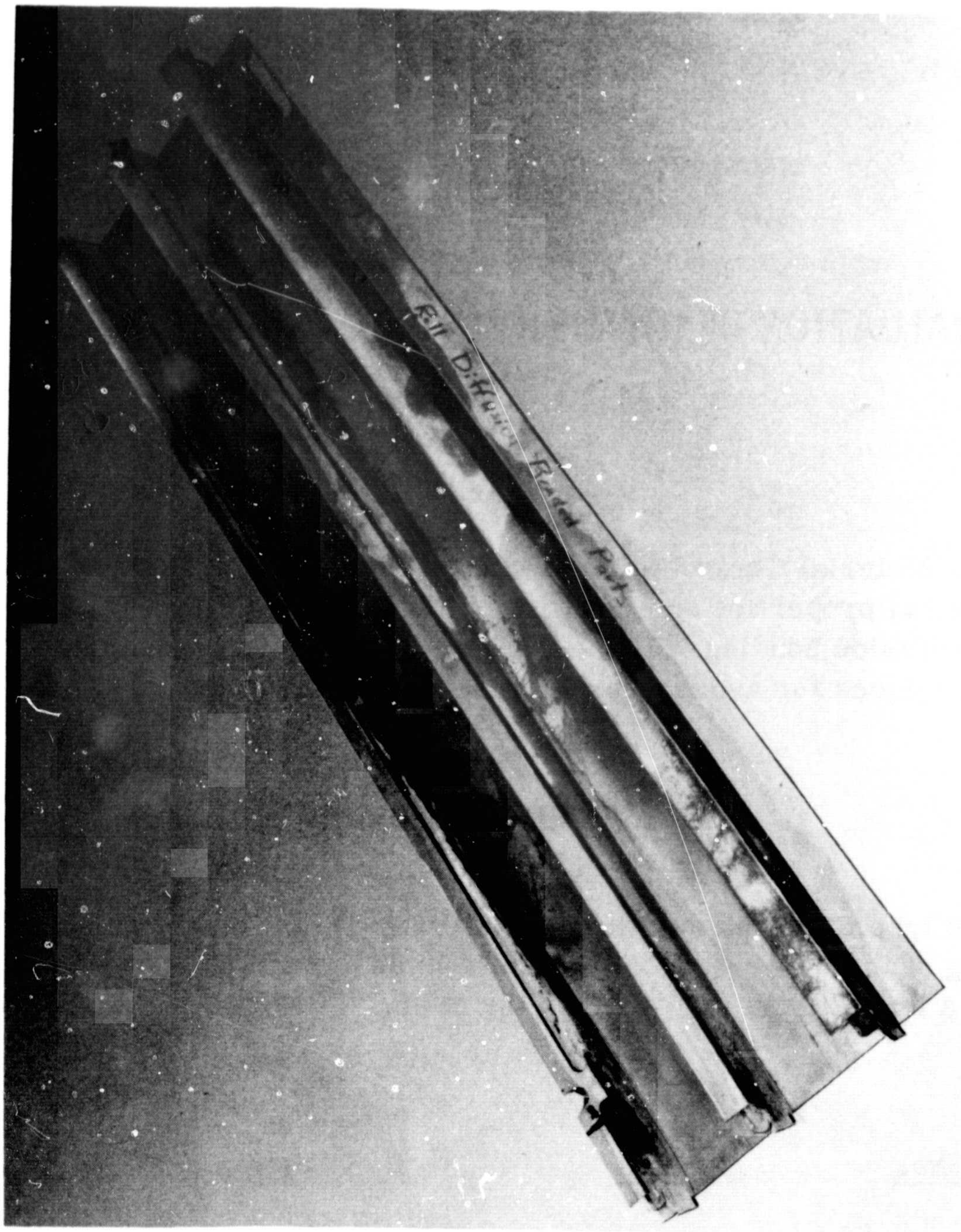


FIGURE 25. TITANIUM PART REMOVED FROM PART C

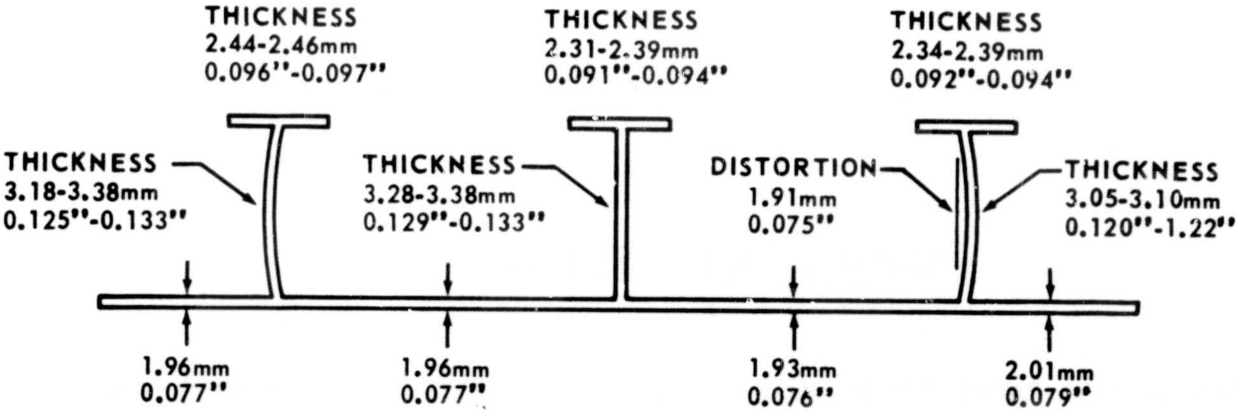


FIGURE 26. CROSS SECTION OF TITANIUM PART SHOWING THICKNESS AND DISTORTION DIMENSIONS

APPENDIX

EVALUATION OF DIFFUSION BONDED TITANIUM SKINS

Introduction

The Material Control Section was requested by R-ME-MMP to evaluate the mechanical properties and microstructure of certain titanium skin sections joined by diffusion bonding. These sections had been roll bonded to evaluate certain techniques for avoiding cracks or sharp radii in the fillet areas.

Mechanical Testing

The type of mechanical testing performed was limited principally to tensile testing of the "T" bonds. Our fixture is designed to secure the top of the "T" while a tensile load is applied to the stem. The breaking loads are shown below:

Speciment No.	Length	Thickness of "T" Stem	Load (pounds)
1	1.032	0.083	4700
2	1.118	0.082	3560
3	1.085	0.084	2190

None of the failures was in the bond itself. All failures were shear type in the top or skin section of the "T". Tensile strength of the stem was 90 600 N/cm^2 (143 000 psi).

Metallographic Evaluation

Photomacrographs and photomicrographs (Figs. A-1 through A-24) were taken of the diffusion bonded joints and the adjacent areas. No evidence of contamination or cracks could be found on the surface of the parent titanium. How-

ever, a few cracks and notches were present at the radii of some fillets. The photomicrographs show that successful bonding had occurred with continuous grain structure across the joint interface.

Conclusions

1. The bonded joints are metallurgically sound with the structure of the joint equivalent to that of the parent metal.

2. The technique of modifying the fillets between the stem and skin sections was at least partly effective; however, cracks and notches were present at most of the fillet sections.

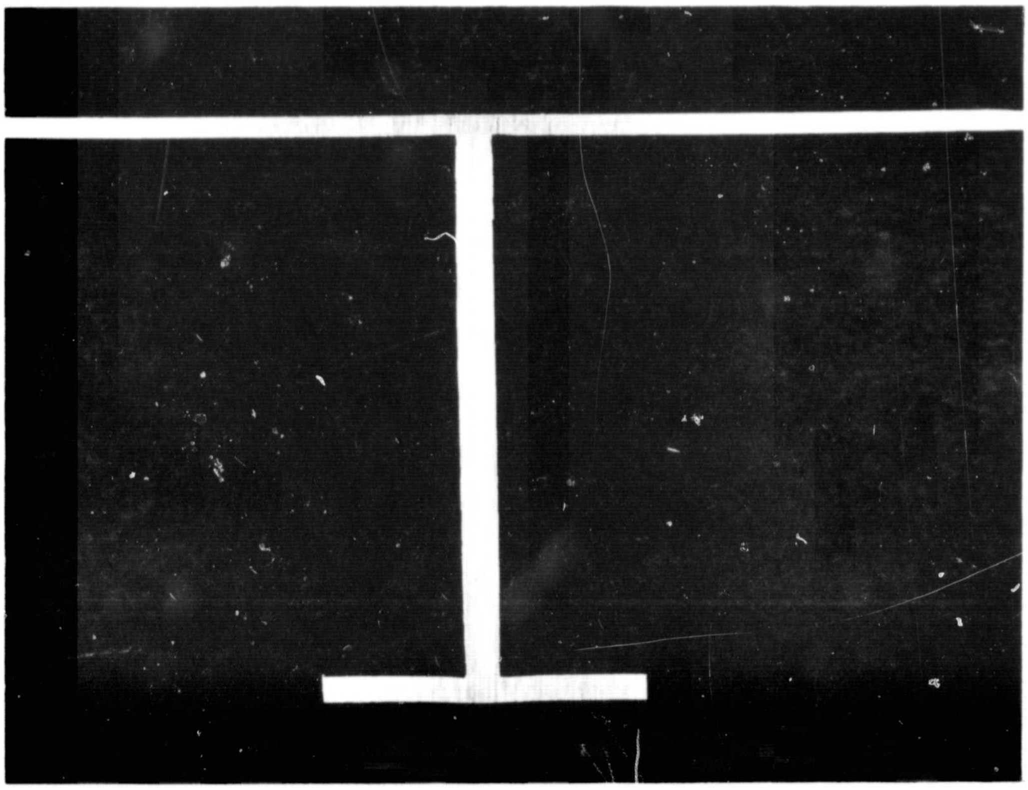


FIGURE A-1. CROSS SECTION OF SAMPLE NO. 1, 1X MAGNIFICATION

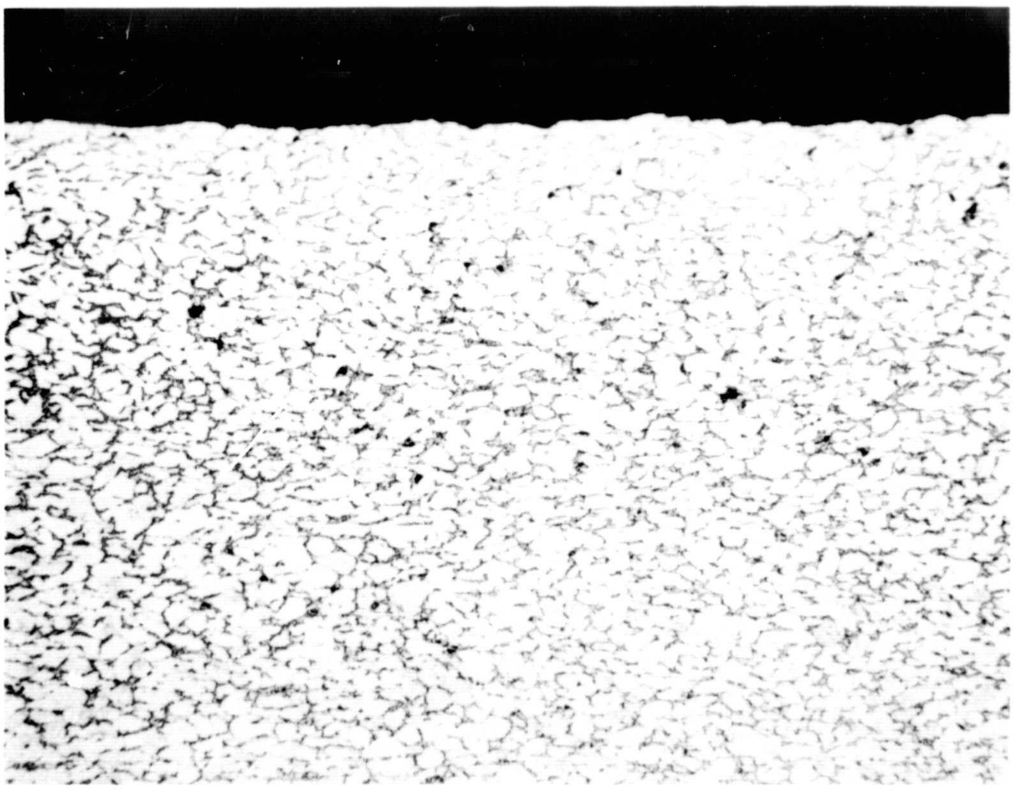


FIGURE A-2. SURFACE OF SAMPLE NO. 1, 200X MAGNIFICATION

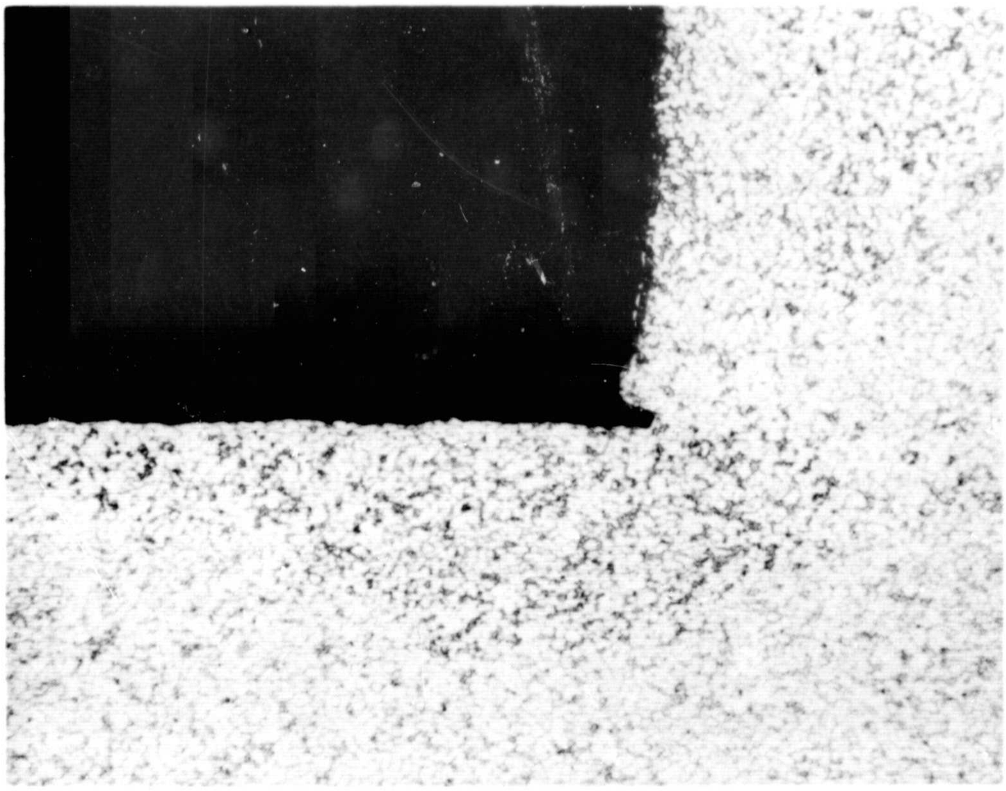


FIGURE A-3. BOND AND FILLET ON BOTTOM SKIN, SAMPLE 1, POSITION 1, 100X MAGNIFICATION

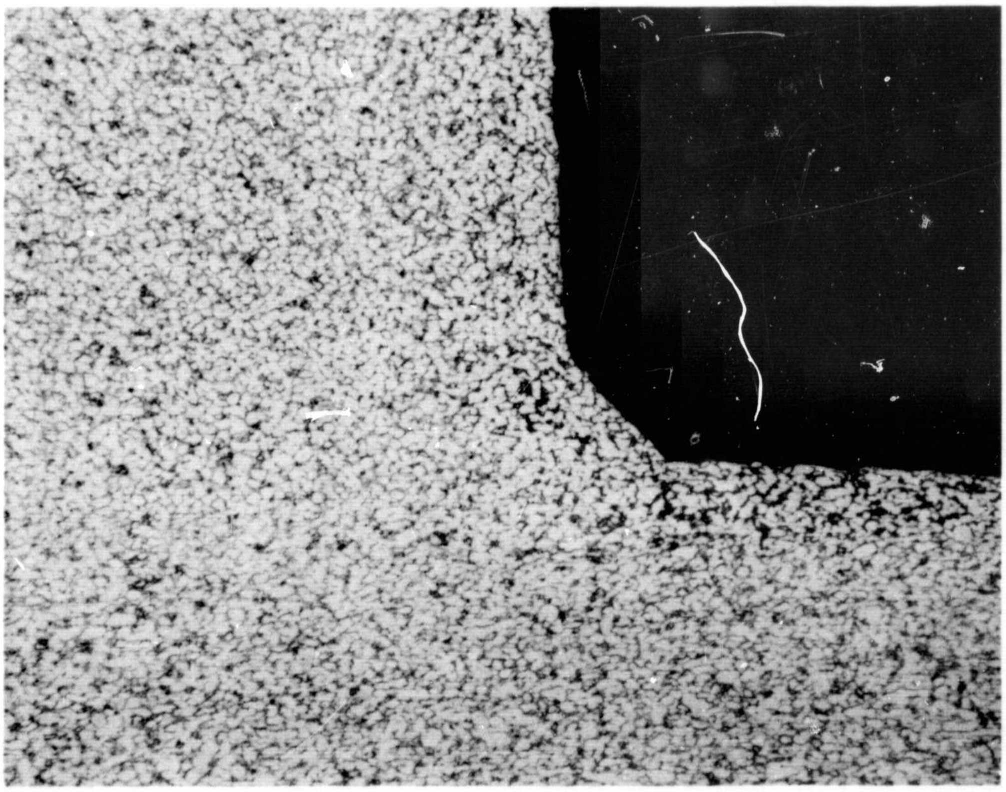


FIGURE A-4. BOND AND FILLET ON BOTTOM SKIN, SAMPLE 1, POSITION 2, 100X MAGNIFICATION

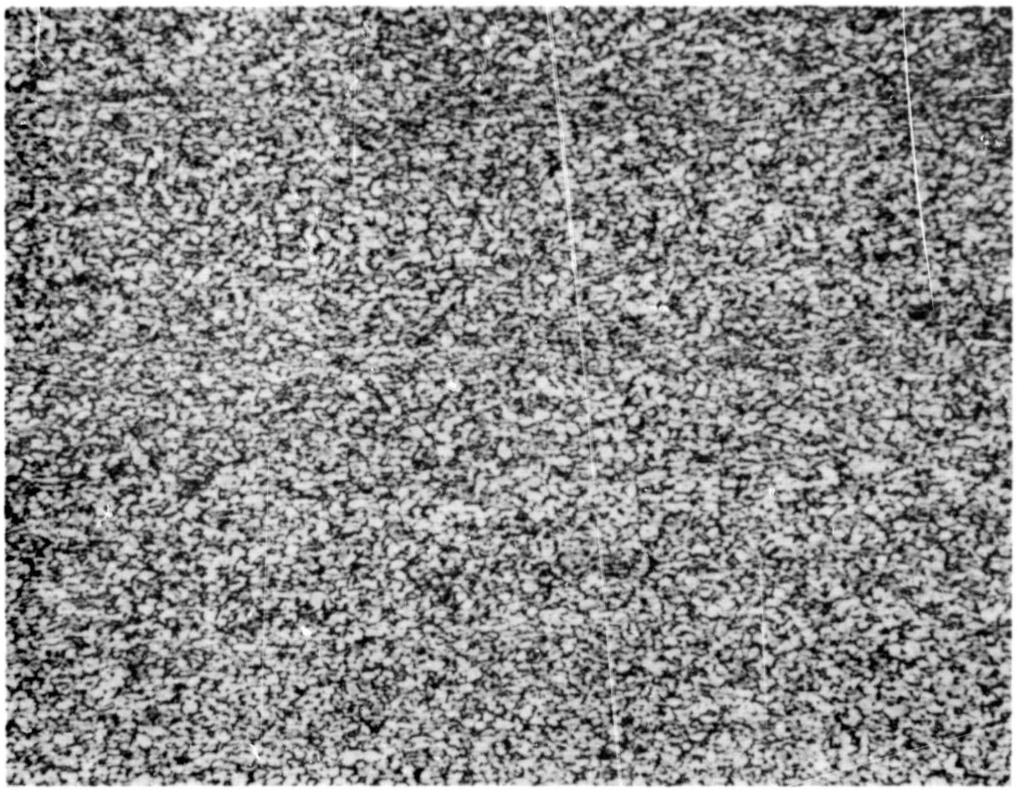


FIGURE A-5. PARENT METAL AT TOP OF "T", SAMPLE 1, 100X MAGNIFICATION

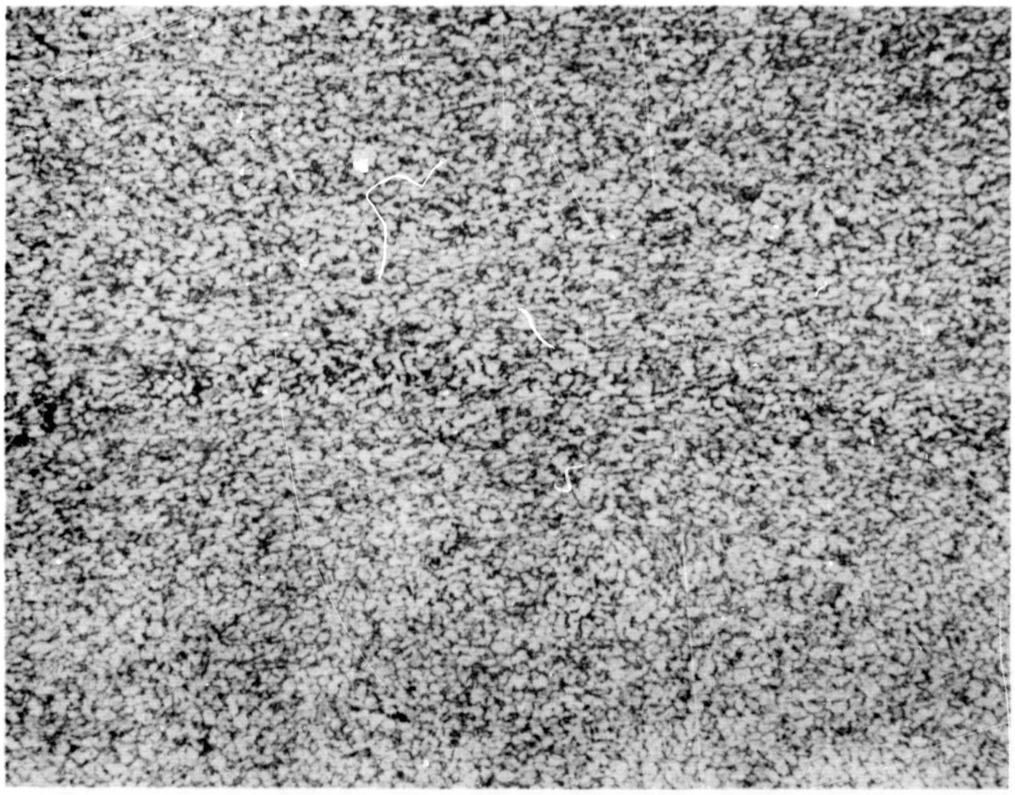


FIGURE A-6. TOP BOND OF SAMPLE 1, 100X MAGNIFICATION

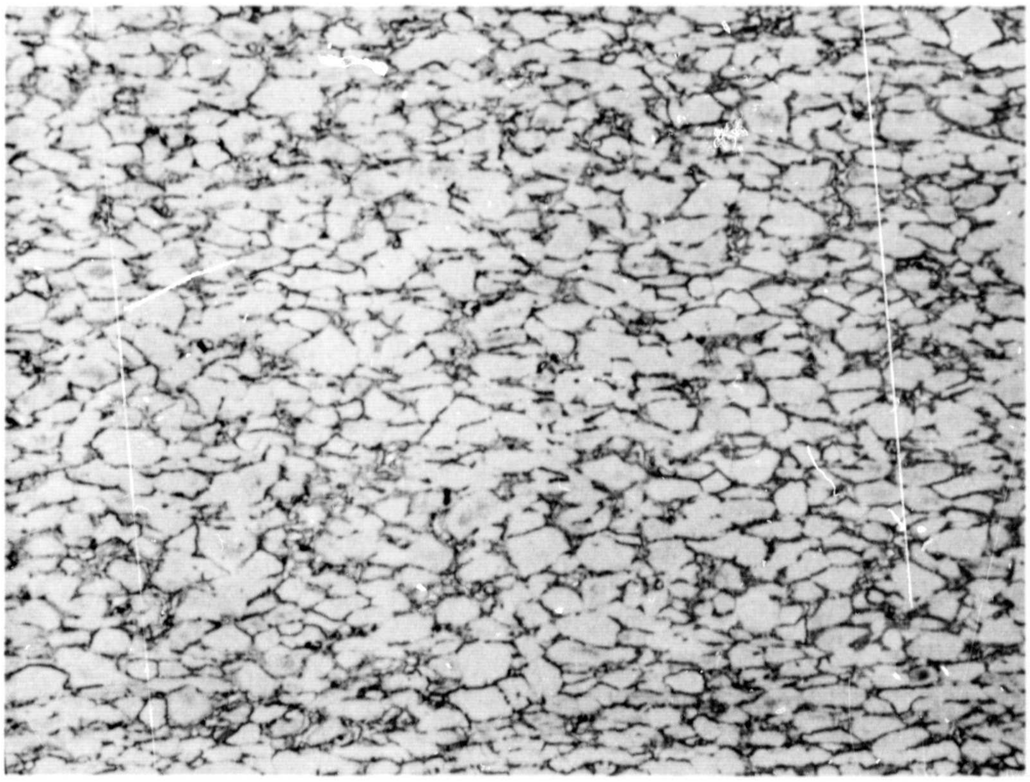


FIGURE A-7. PARENT METAL OF "T" STIFFENER, SAMPLE 1, 500X MAGNIFICATION

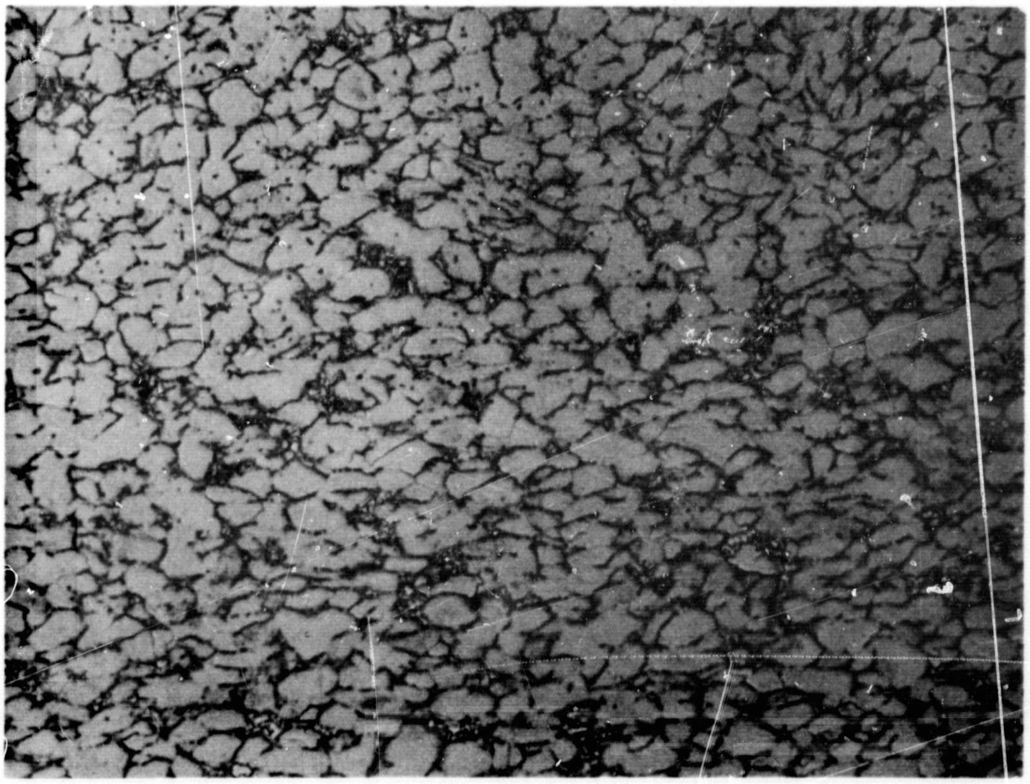


FIGURE A-8. TOP BOND JOINT, SAMPLE 1, 500X MAGNIFICATION

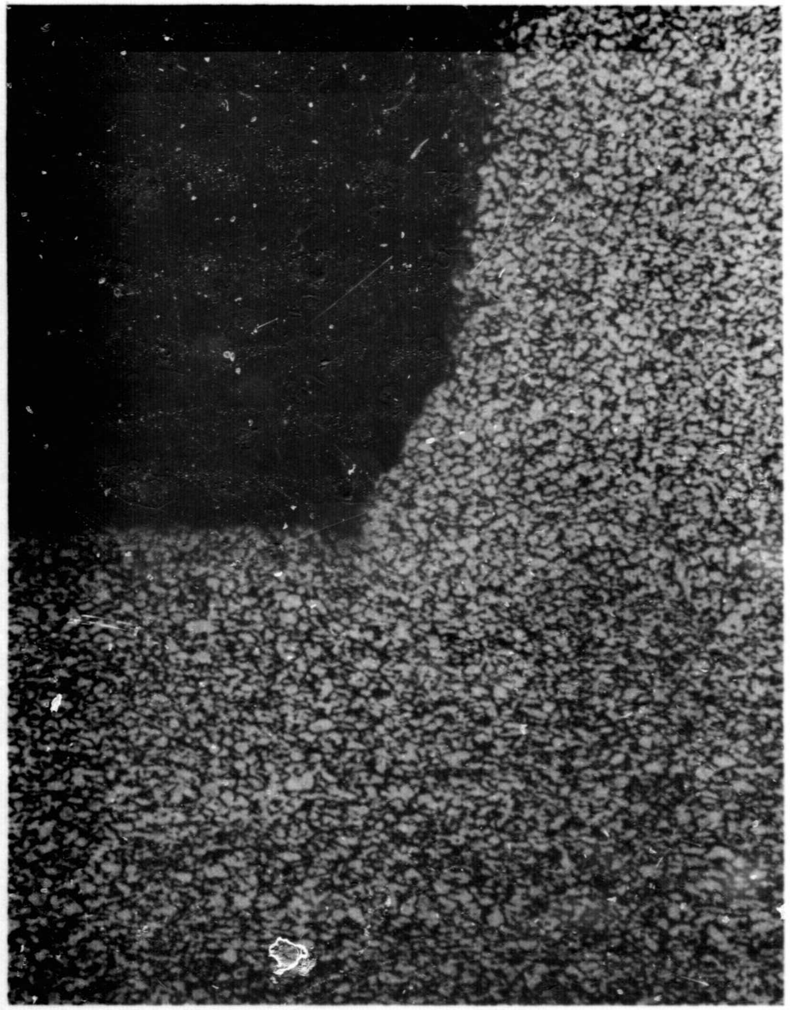


FIGURE A-9. BOND AND FILLET NOTCH ON TOP SKIN OF SAMPLE 1, POSITION 1, 100X MAGNIFICATION

FIGURE A-10. BOND AND FILLET NOTCH ON TOP SKIN OF SAMPLE 1, POSITION 2, 100X MAGNIFICATION

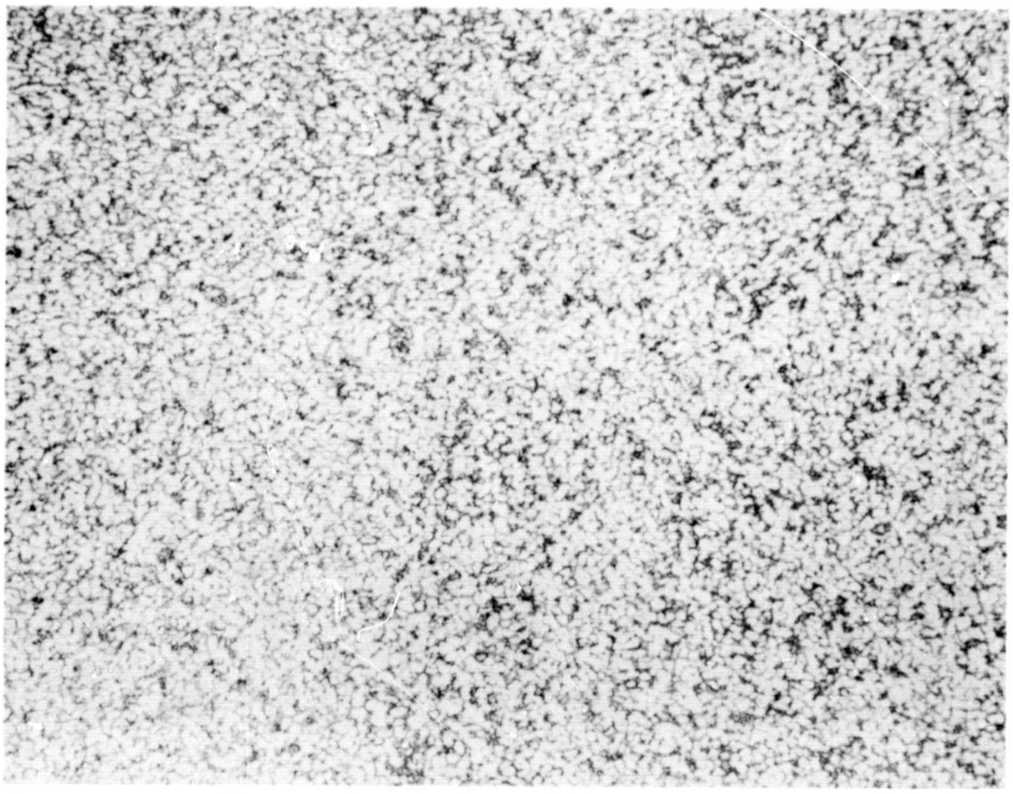


FIGURE A-11. BONDED AREA AT BOTTOM POSITION OF SAMPLE 1, 100X MAGNIFICATION

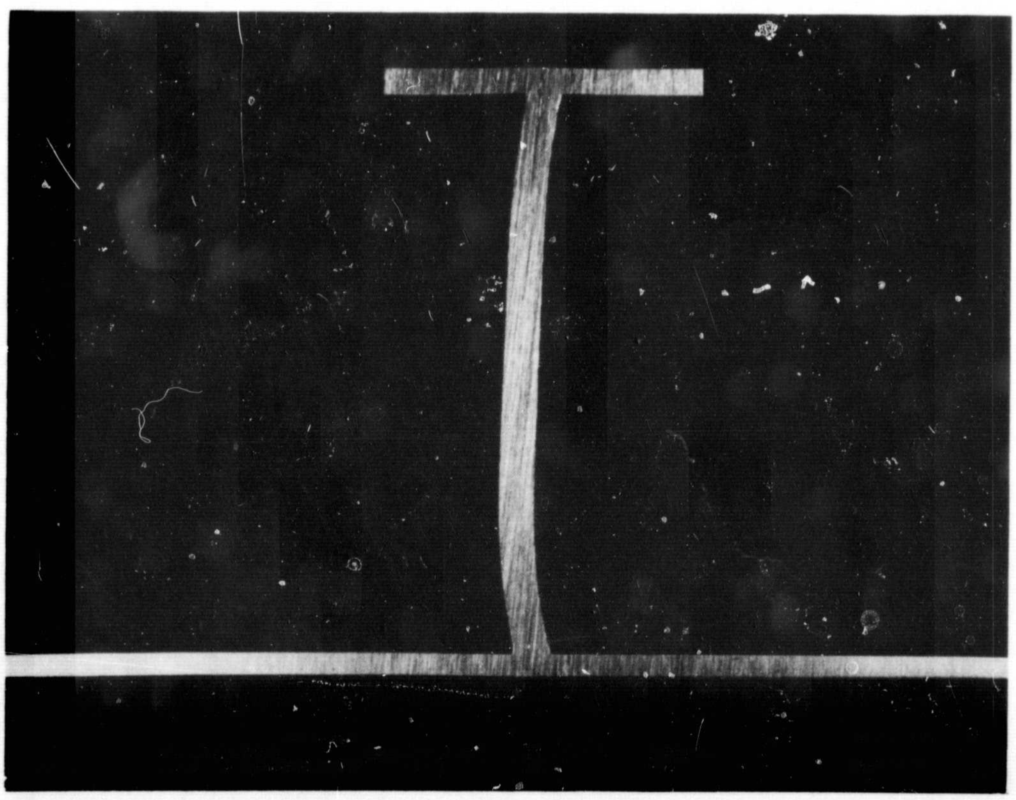


FIGURE A-12. CROSS SECTION OF SAMPLE 2, 1X MAGNIFICATION

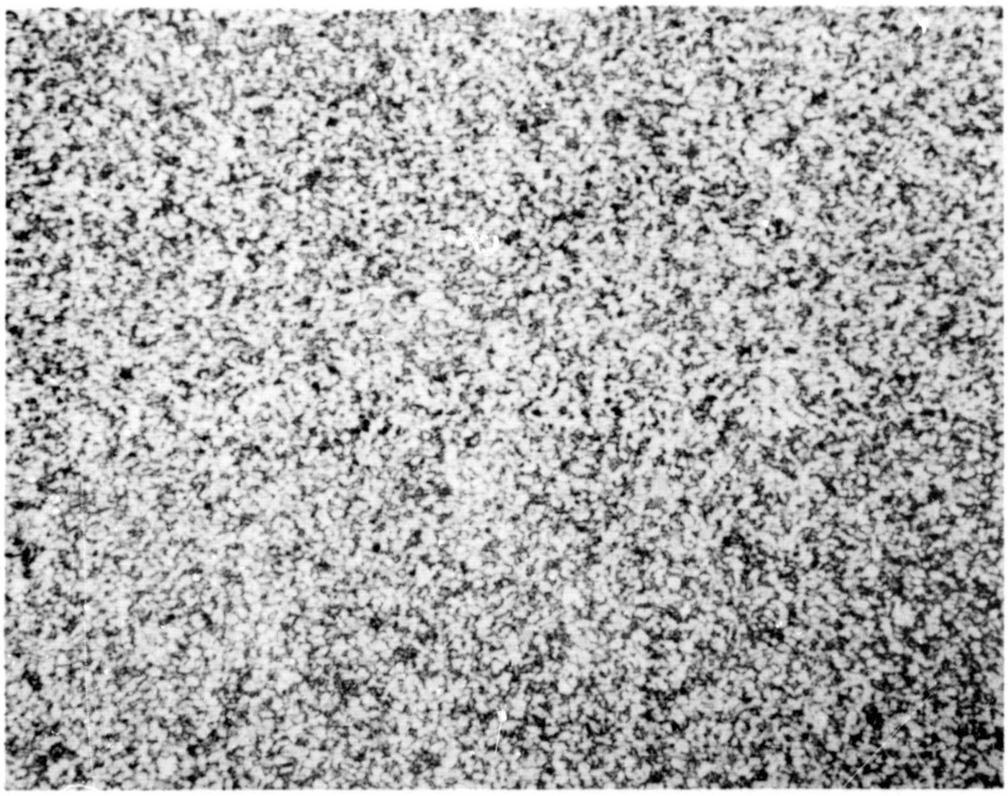


FIGURE A-13. BONDED JOINT ON TOP SECTION OF SAMPLE 2, 100X MAGNIFICATION

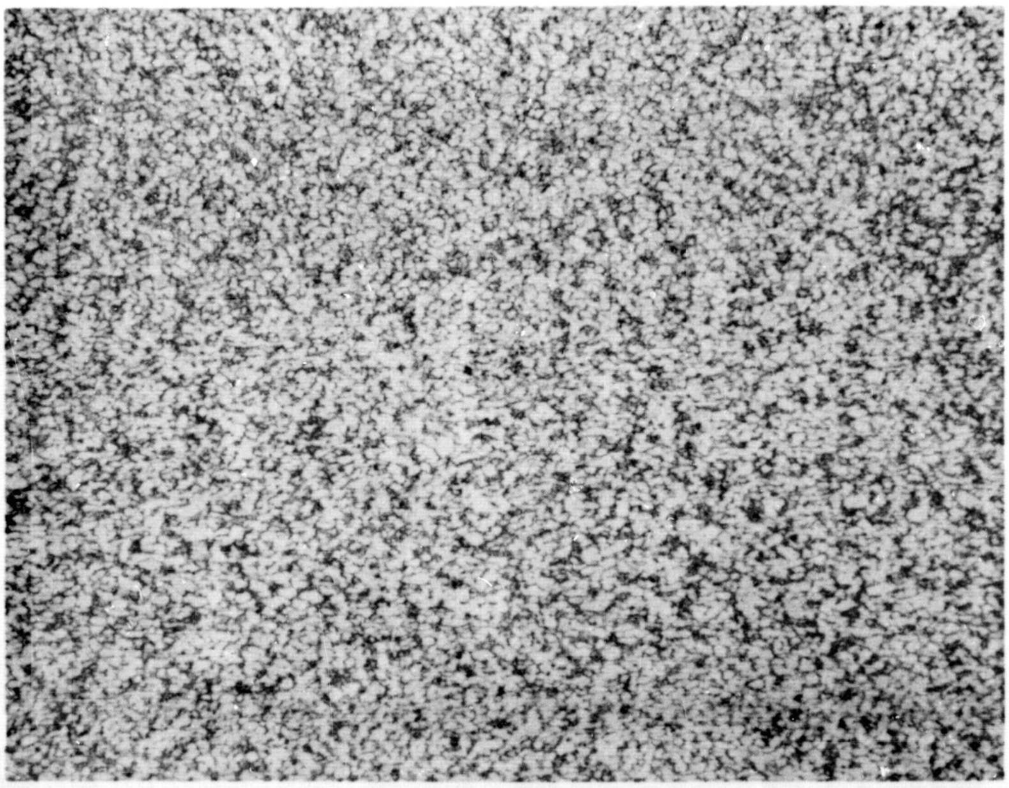


FIGURE A-14. BONDED JOINT ON BOTTOM SECTION OF SAMPLE 2, 100X MAGNIFICATION

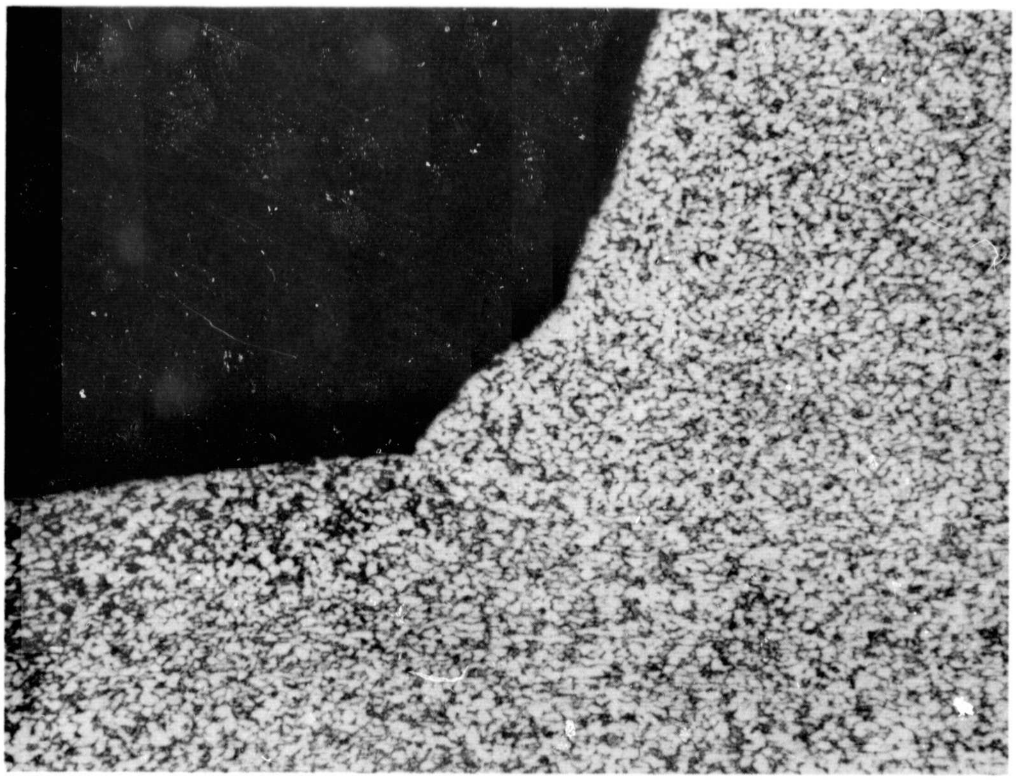


FIGURE A-15. BOND AND FILLET NOTCH ON BOTTOM SKIN OF SAMPLE 2, POSITION 1, 100X MAGNIFICATION

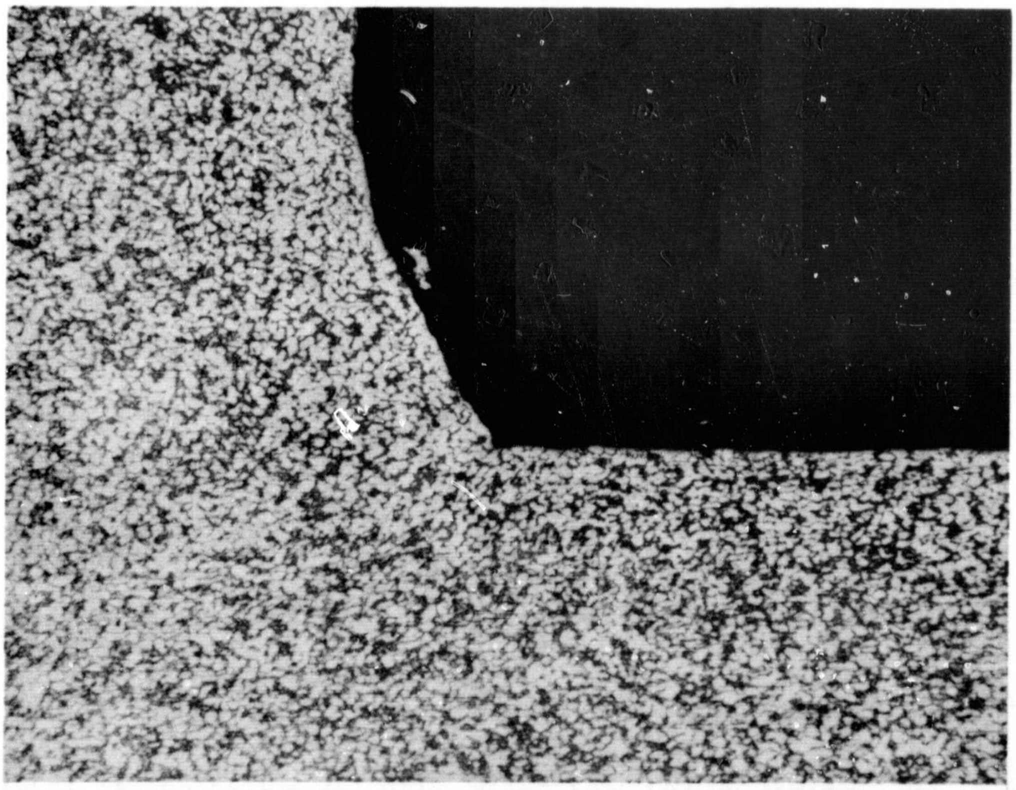


FIGURE A-16. BOND AND FILLET NOTCH ON BOTTOM SKIN OF SAMPLE 2, POSITION 2, 100X MAGNIFICATION

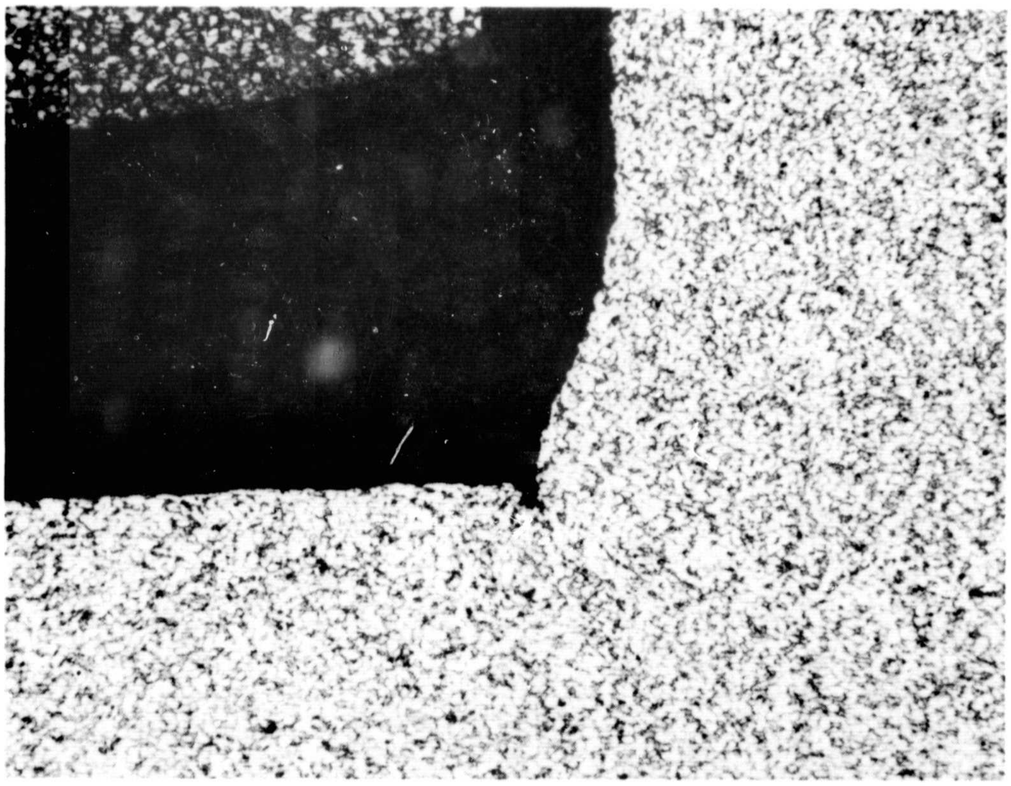


FIGURE A-17. BOND AND CRACK ON TOP OF SAMPLE 2, POSITION 1, 100X MAGNIFICATION

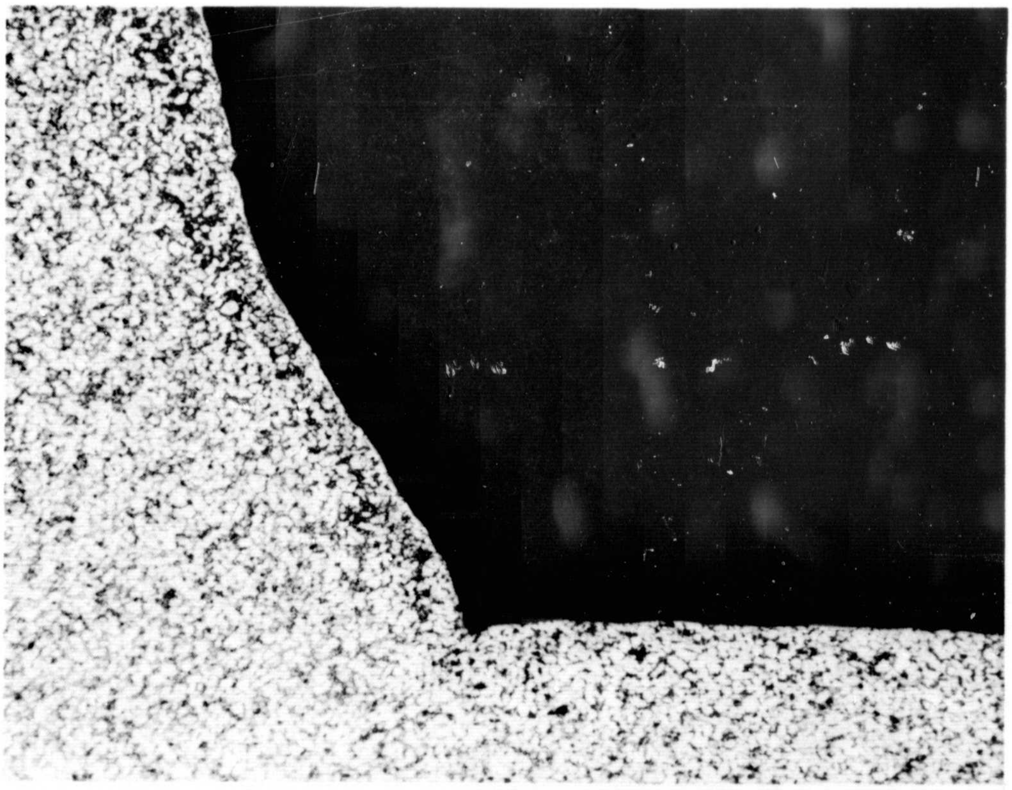


FIGURE A-18. BOND AND CRACK ON TOP OF SAMPLE 2, POSITION 2, 100X MAGNIFICATION

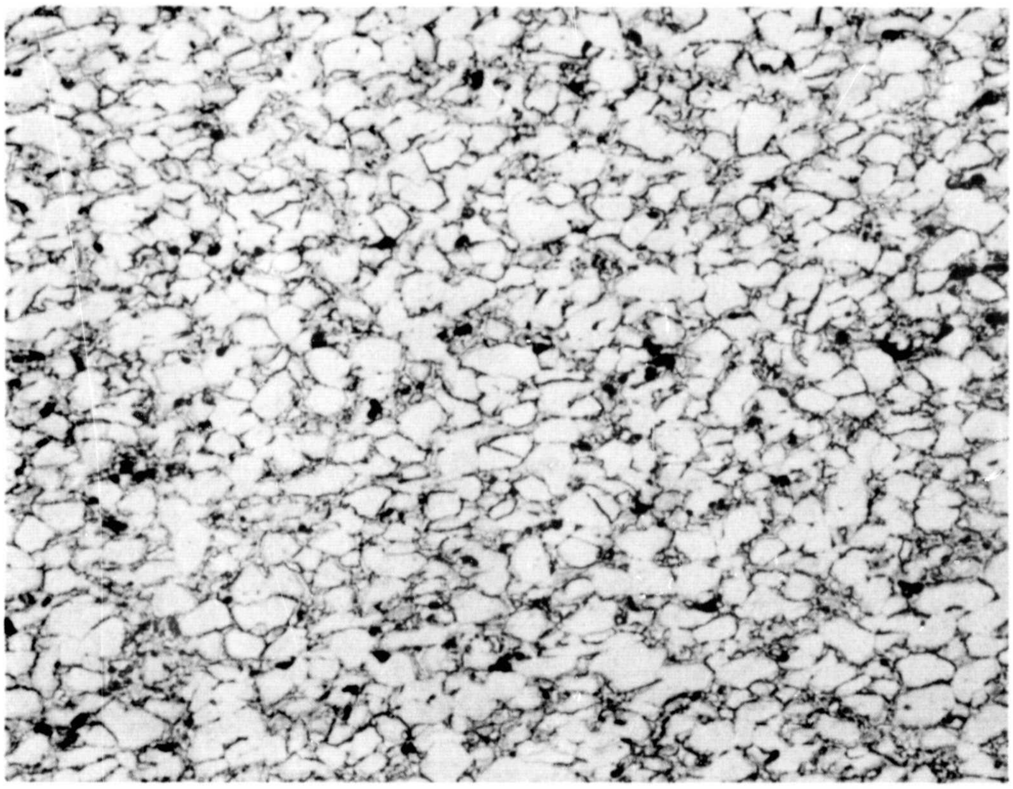


FIGURE A-19. CROSS SECTION OF STIFFENER, SAMPLE 2, 500X MAGNIFICATION

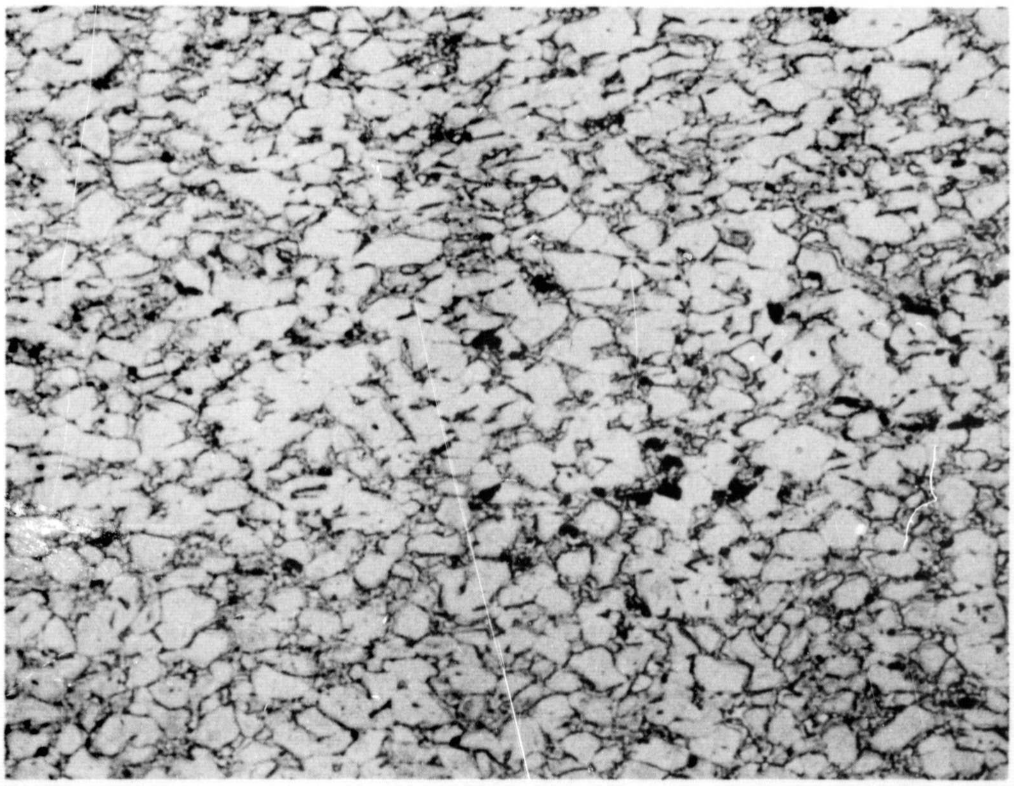


FIGURE A-20. CROSS SECTION OF BONDED JOINT AT TOP POSITION OF SAMPLE 2, 500X MAGNIFICATION

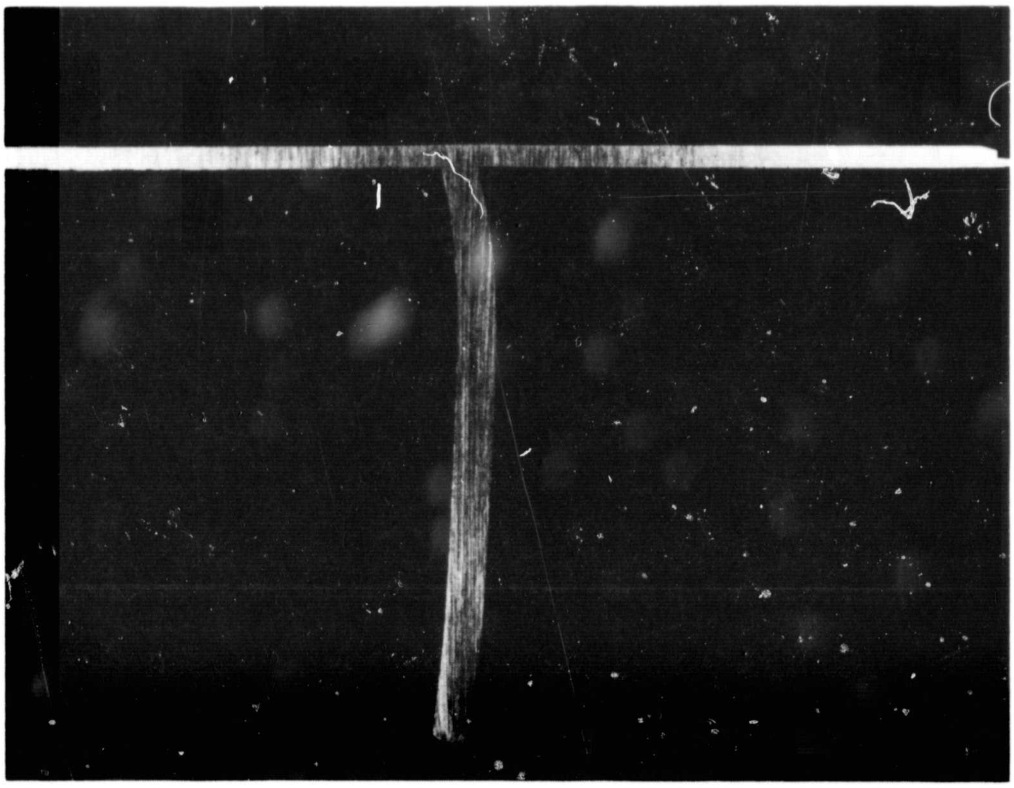


FIGURE A-21. CROSS SECTION OF SAMPLE 3, 1X MAGNIFICATION

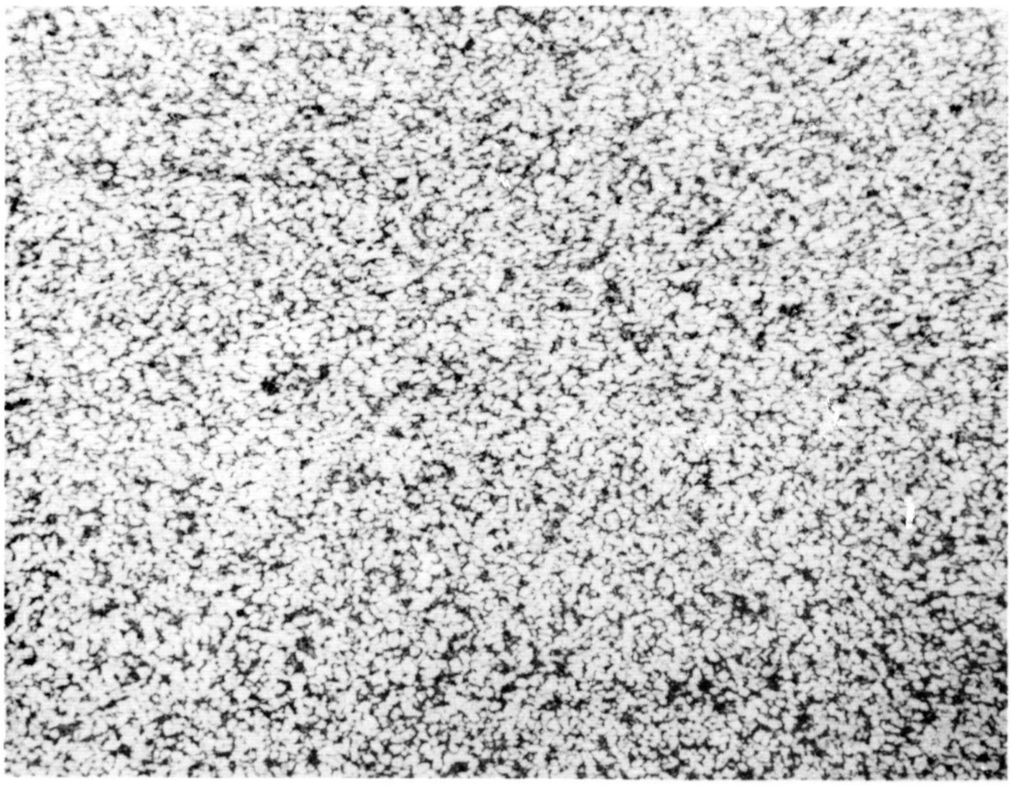


FIGURE A-22. CROSS SECTION OF BONDED JOINT OF SAMPLE 3, 100X MAGNIFICATION

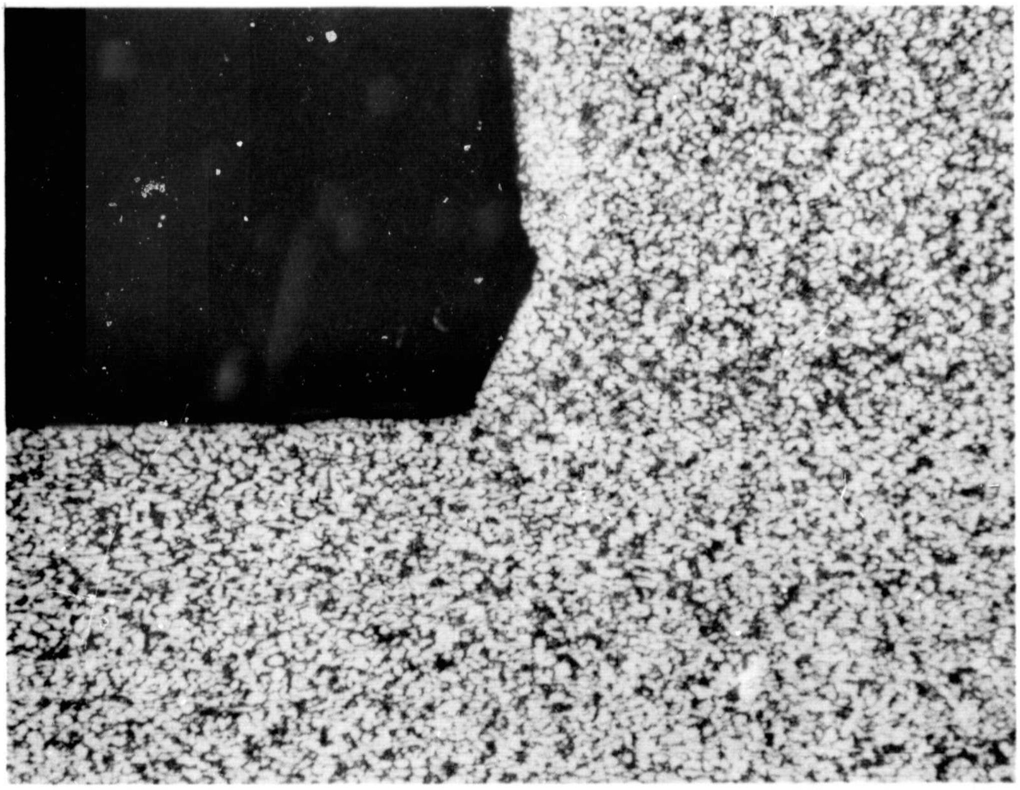


FIGURE A-23. BOND AND GOOD FILLET OF SAMPLE 3, POSITION 1, 100X MAGNIFICATION

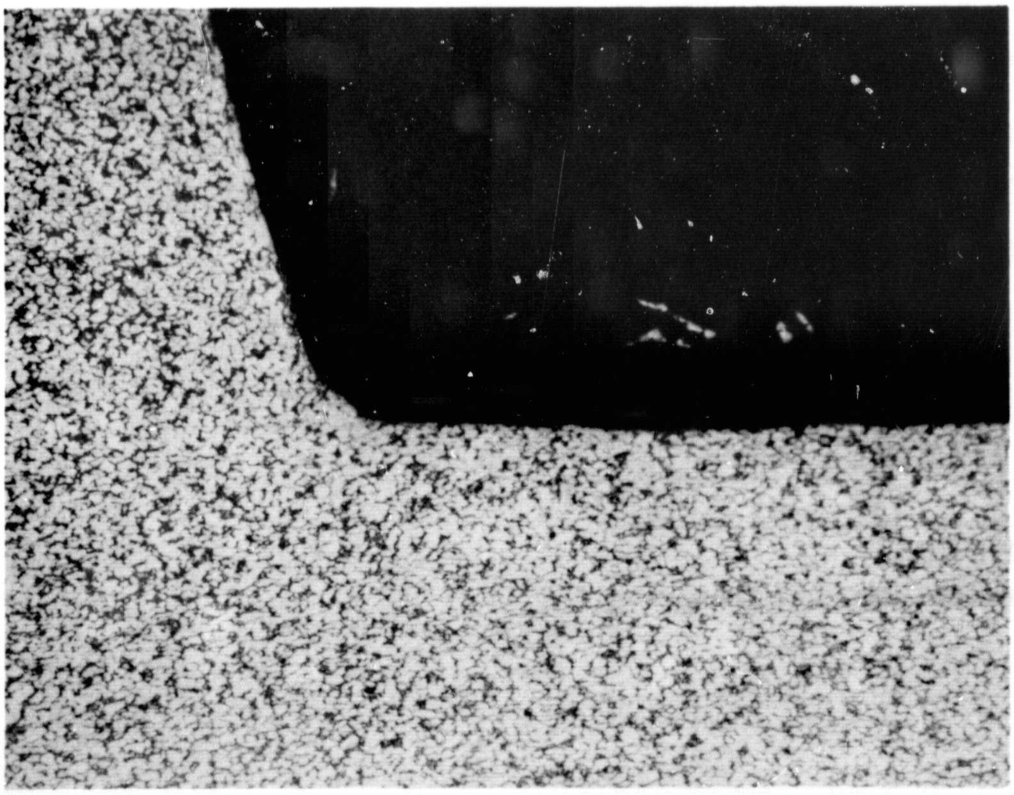


FIGURE A-24. BOND AND GOOD FILLET OF SAMPLE 3, POSITION 2, 100X MAGNIFICATION

June 28, 1968 | APPROVAL | IN-ME-68-4

ROLL DIFFUSION BONDING DEVELOPMENT

by

Carl M. Wood

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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